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Control of wind power plants

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Control of wind power plants

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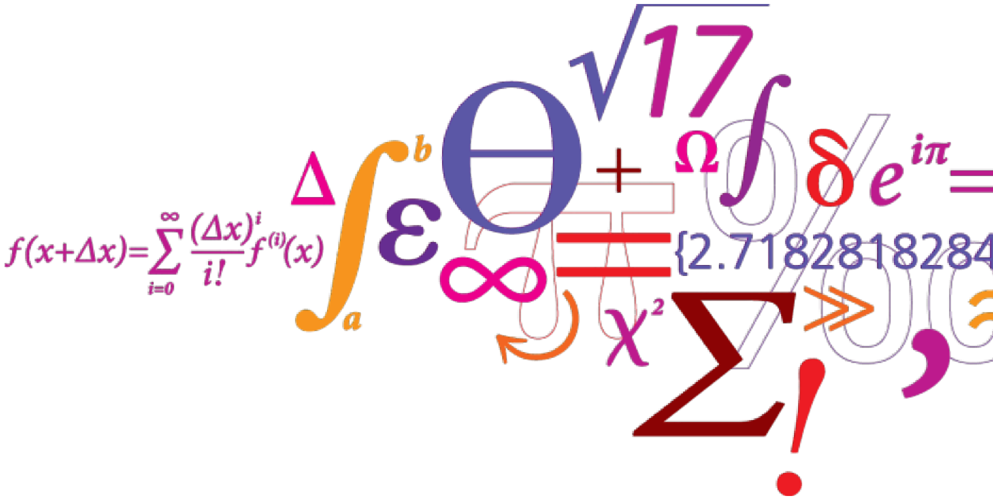

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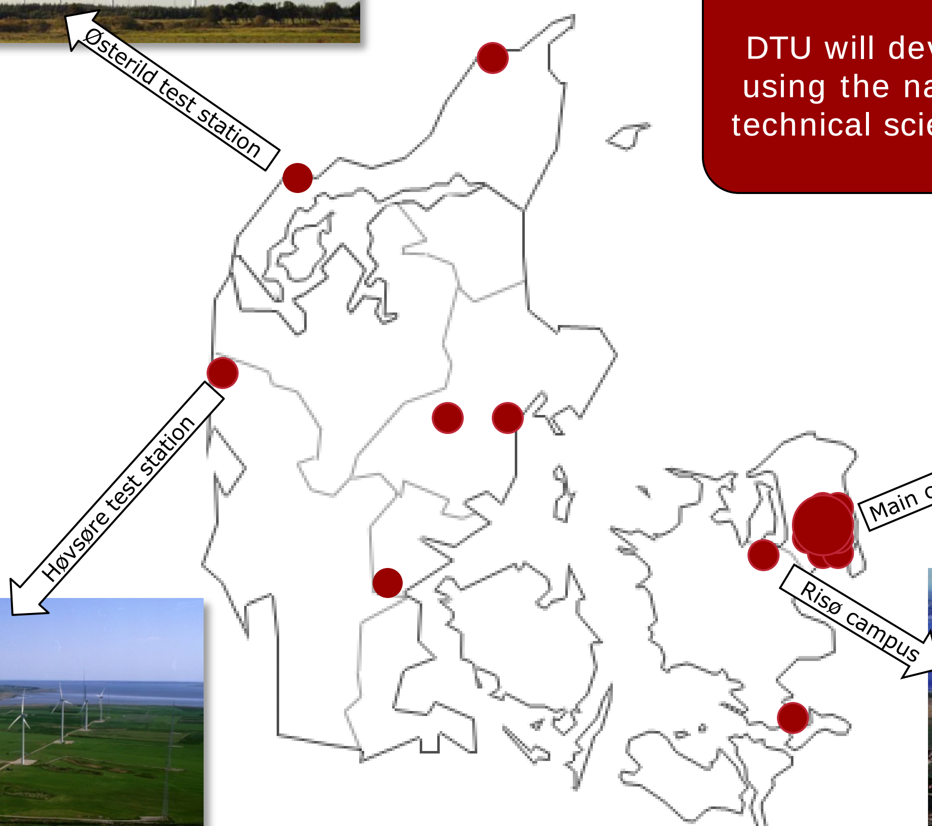

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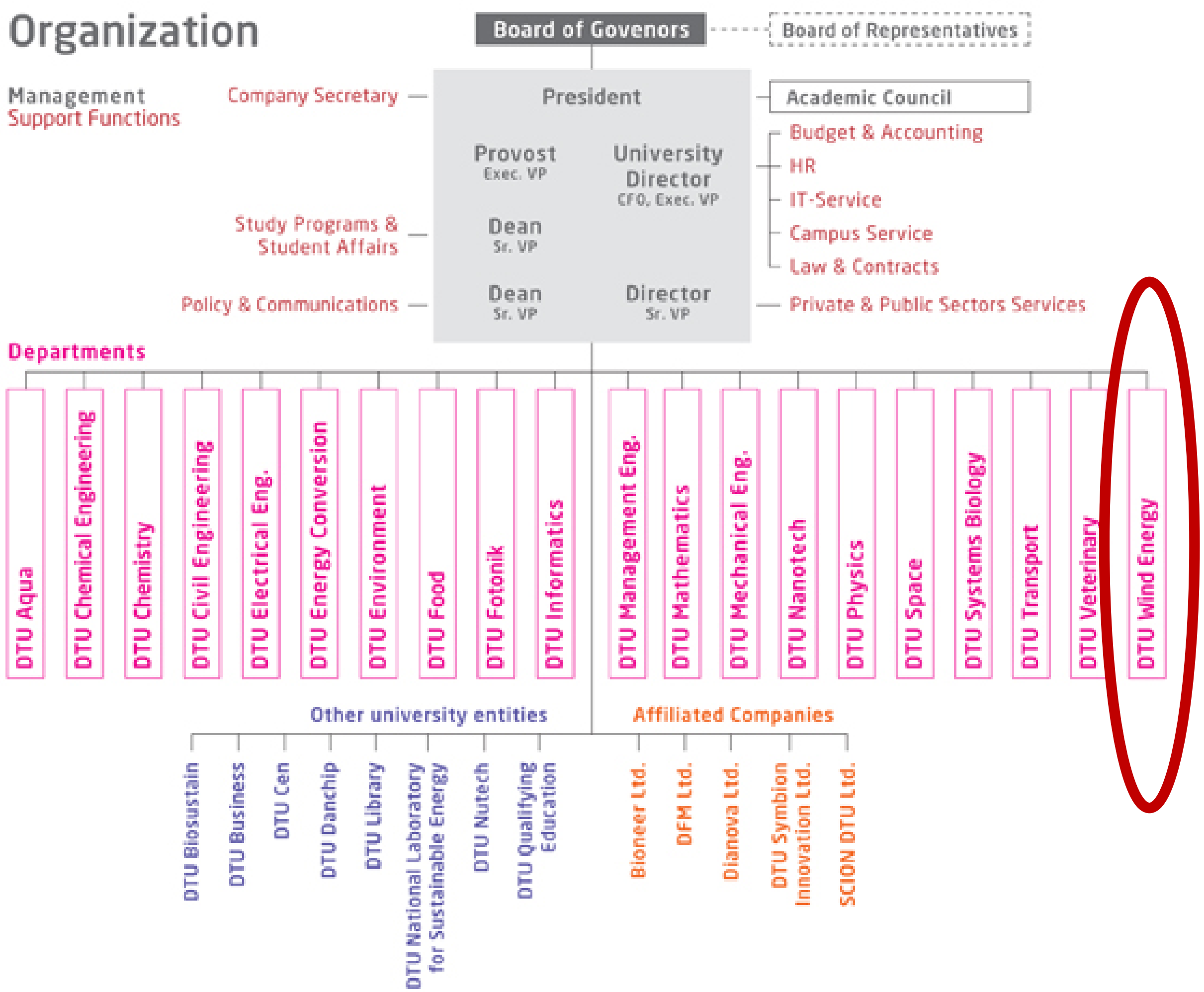

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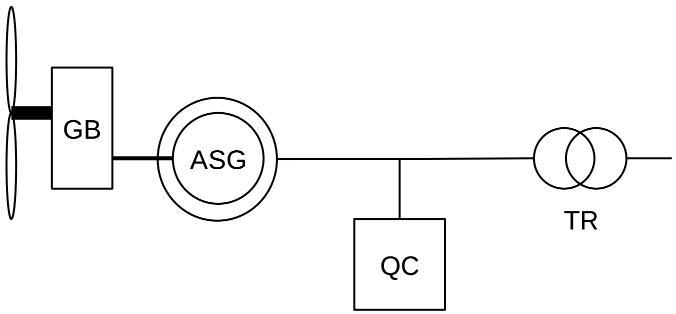
DTU Wind Energy
Department of Wind Energy

- Composites and Materials Mechanics
- Materials Science and Characterisation
- Fluid Mechanics
- Test and Measurements
- Wind Turbines Structures
- Aerolastic Design
- Meteorology
- Wind Energy Systems

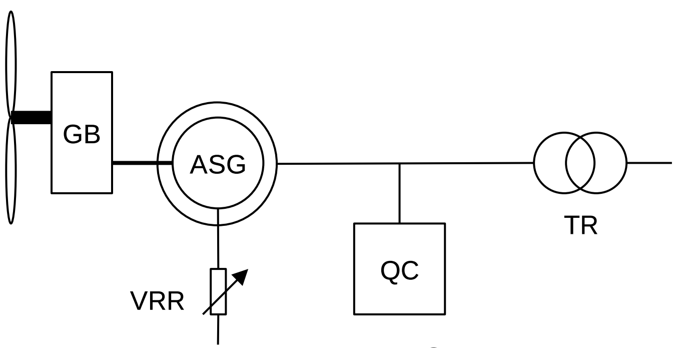
Control issues

- List purposes of controlling wind power plants:

4 wind turbine types



Type 1



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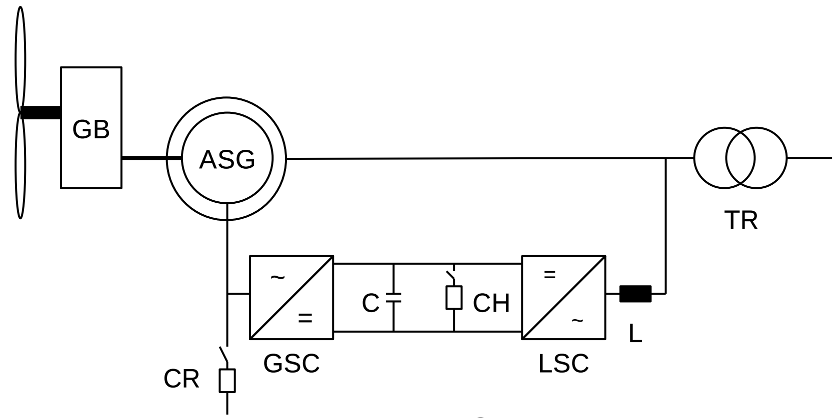

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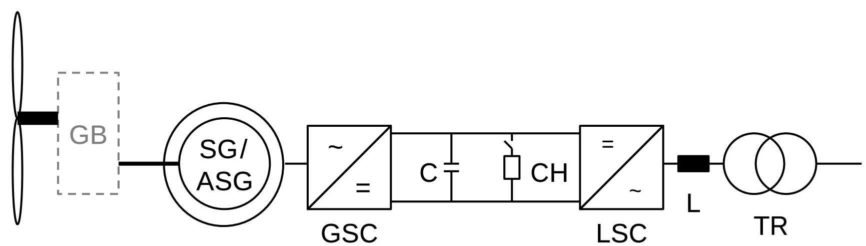


Type 4

ASG: Asynchronous generator
GB: Gearbox
QC: Reactive power compensation
SG: Synchronous generator
TR: Transformer
VRR: Variable rotor resistance

GSC: Generator side converter
LSC: Line side converter
CR: Crowbar
C: DC link capacitor
CH: Chopper
L: Series inductance

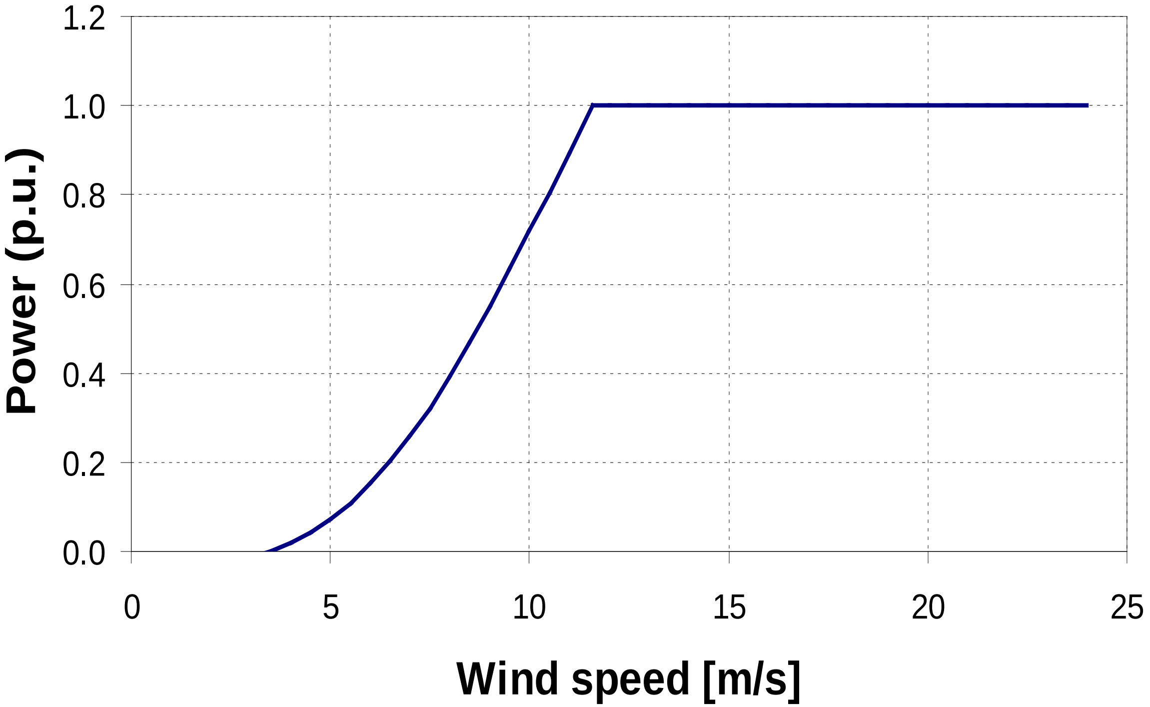
Outline

- General about wind turbine control
  - blade angle control
  - rotor speed control
- Electrical design and controllability / control strategies
  - fixed speed
  - variable speed
- Control examples
  - Normal wind turbine operation control
    - Fixed speed example (Active stall control)
    - Variable speed example (doubly-fed and pitch control)
  - Fault ride through wind turbine control
    - Active stall
    - Doubly fed
  - Wind turbine load reducing control
  - Wind farm control

Aerodynamic power – power curve

- P : aerodynamic power [W]
- U : wind speed

Power curve based on 10 min averages

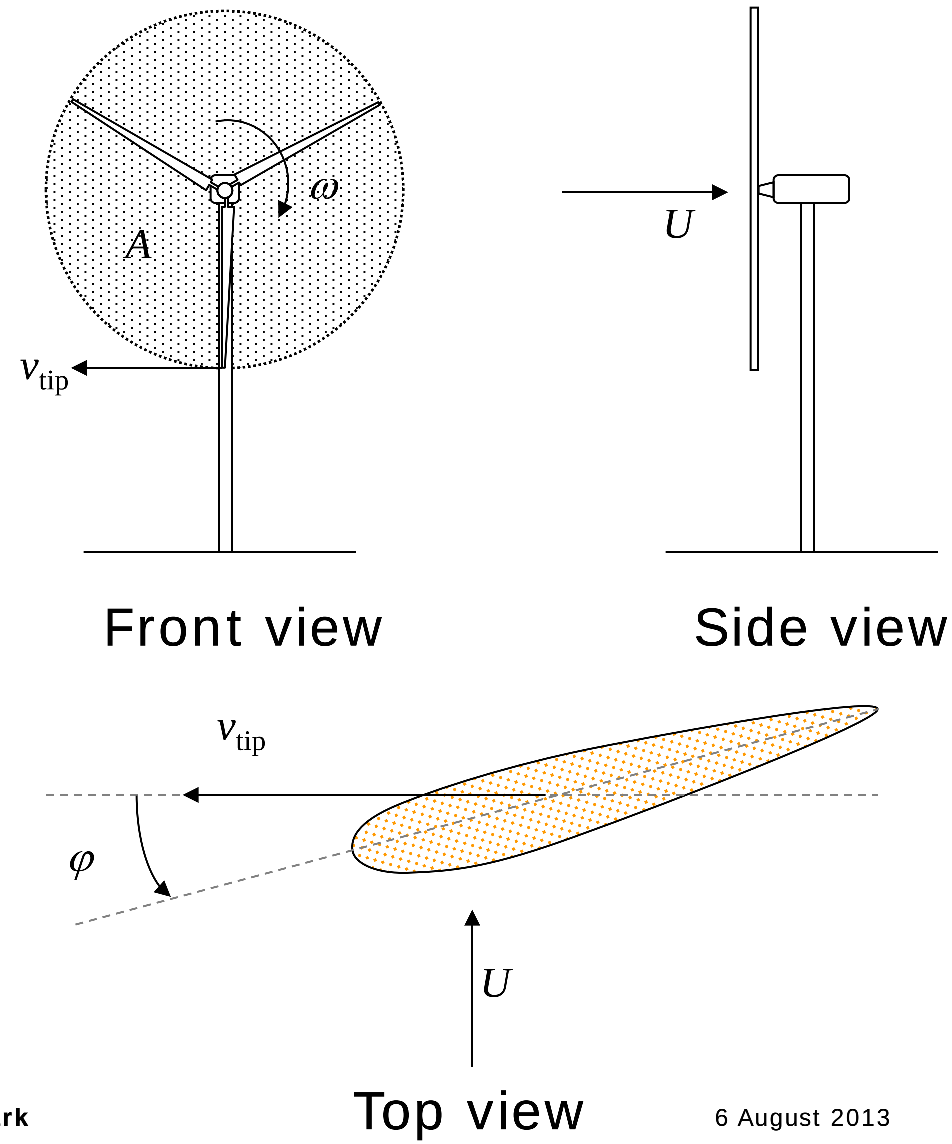


Aerodynamic power – power coefficient

$$P = \frac{1}{2}\rho A U^3 C_p(\lambda, \varphi)$$

- P : **aerodynamic power [W]**
- ρ : **air density [kg / m³]**
- A : **rotor (swept) area**
- U : **wind speed**
- C_p : **power coefficient**
- φ : **blade pitch angle**
- λ : **tip speed ratio**

$$\lambda = \frac{v_{\text{tip}}}{U} = \frac{\omega \cdot R}{U}$$



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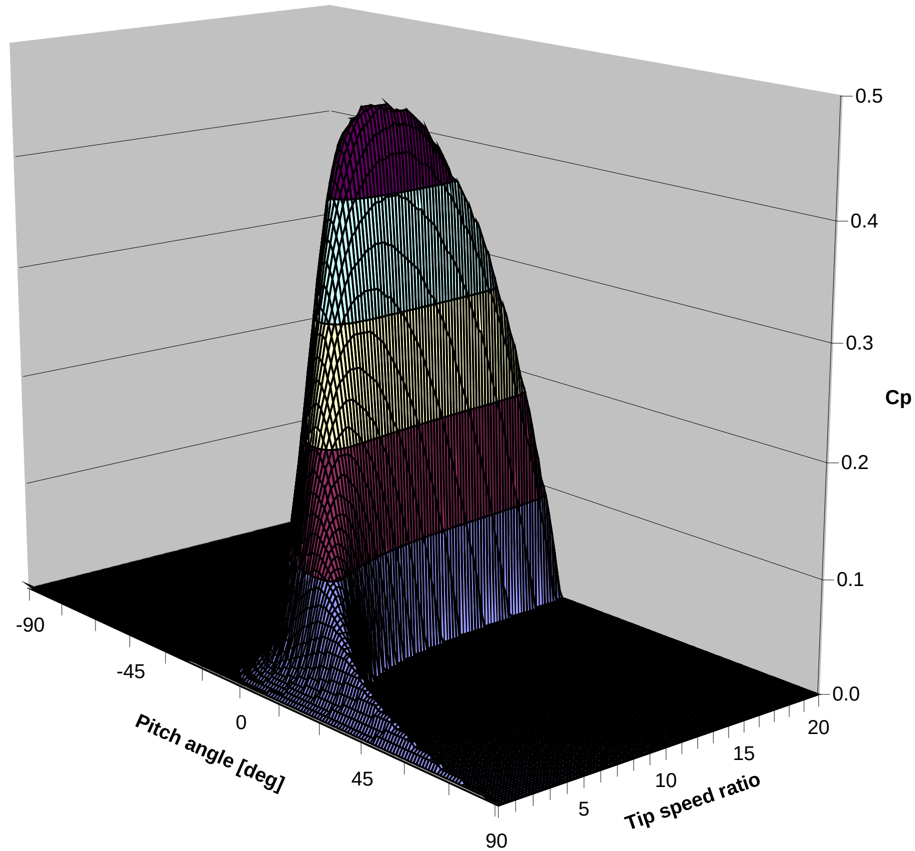
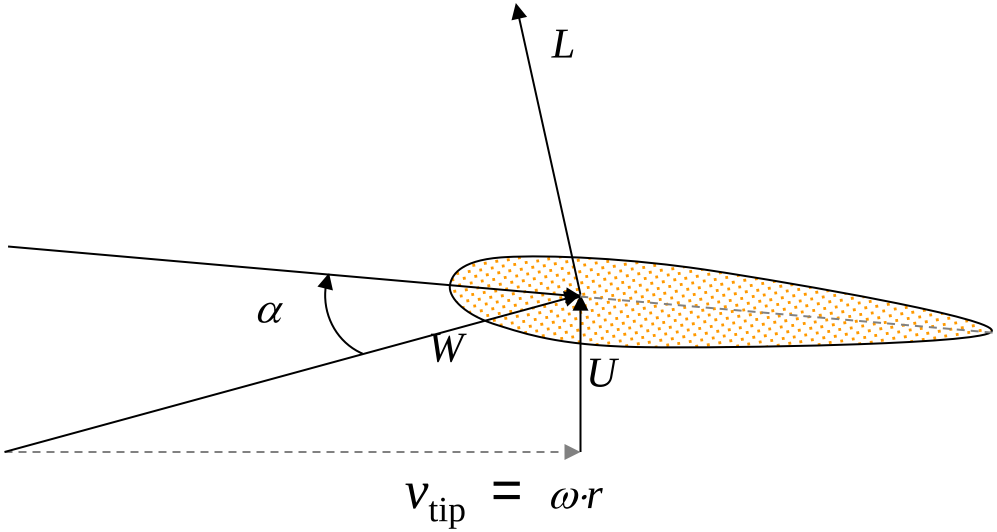
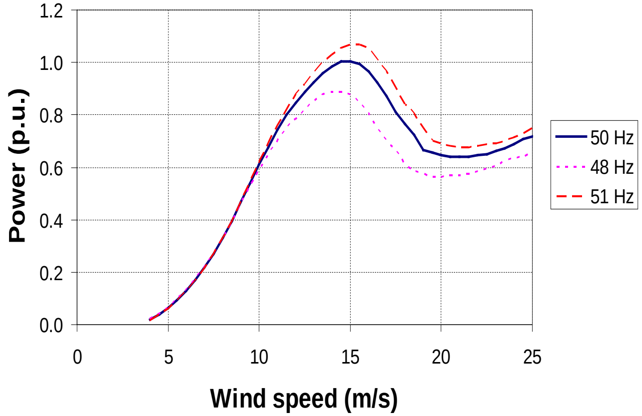
- C_p : **power coefficient**



Passive stall control



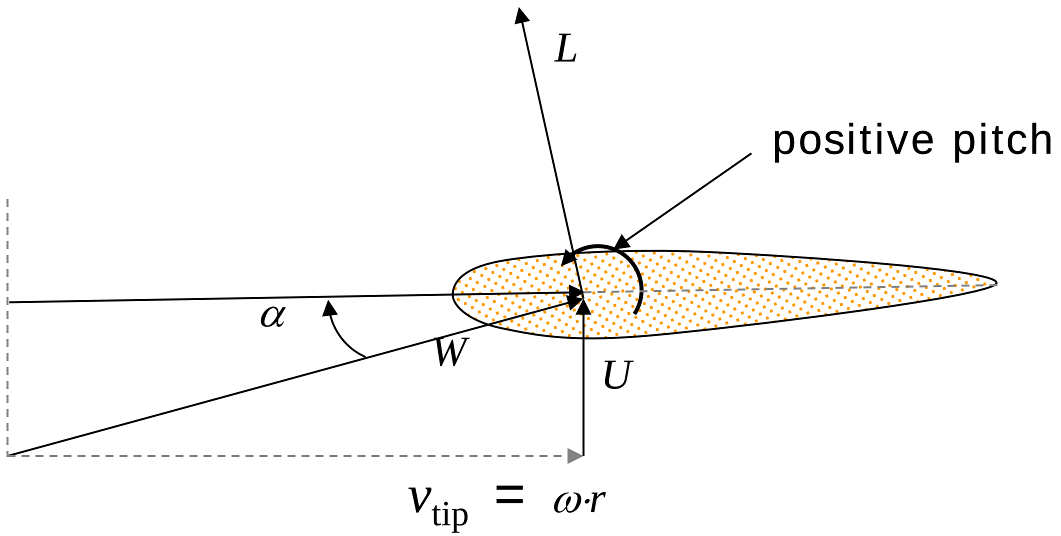


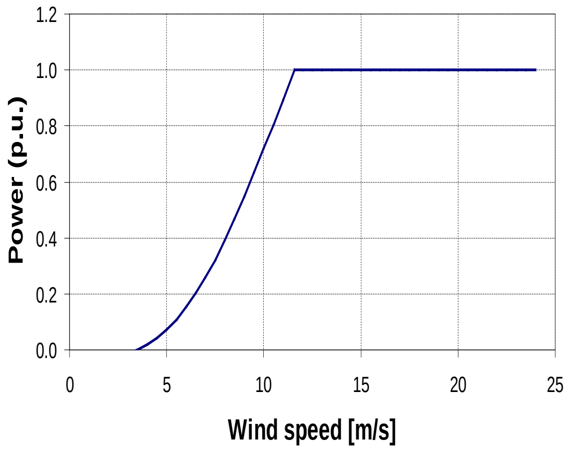
W: relative speed seen from rotating blade
α: angle of attack
L: lift

Power curve sensitive to

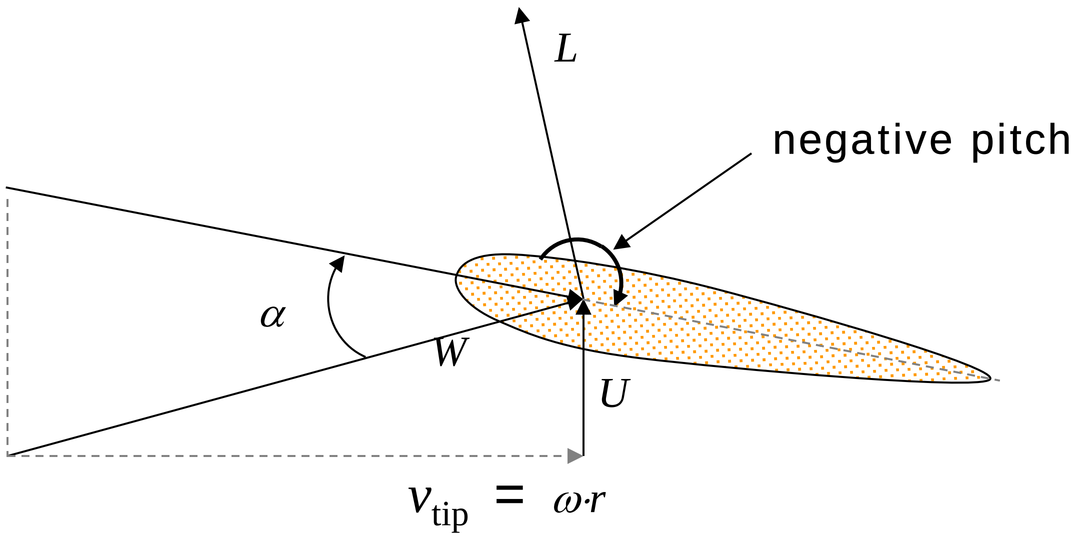
- electrical grid frequency (3rd order)
- air density (1st order)
- dirt on blades

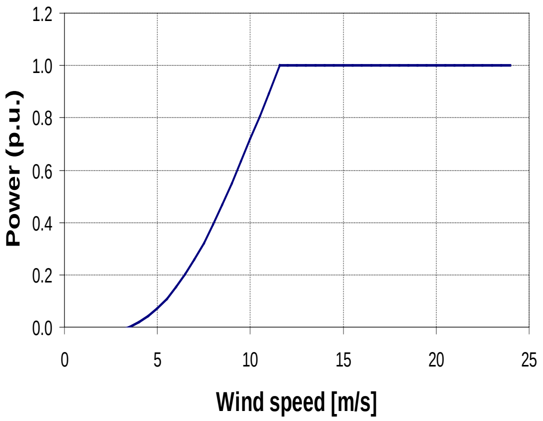
Pitch control





Aktiv stall control (or kombi-stall)

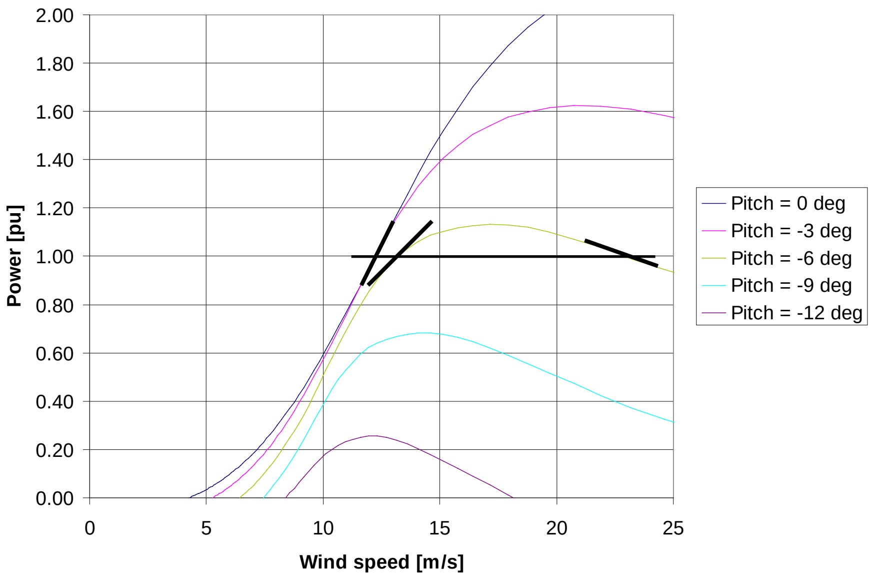


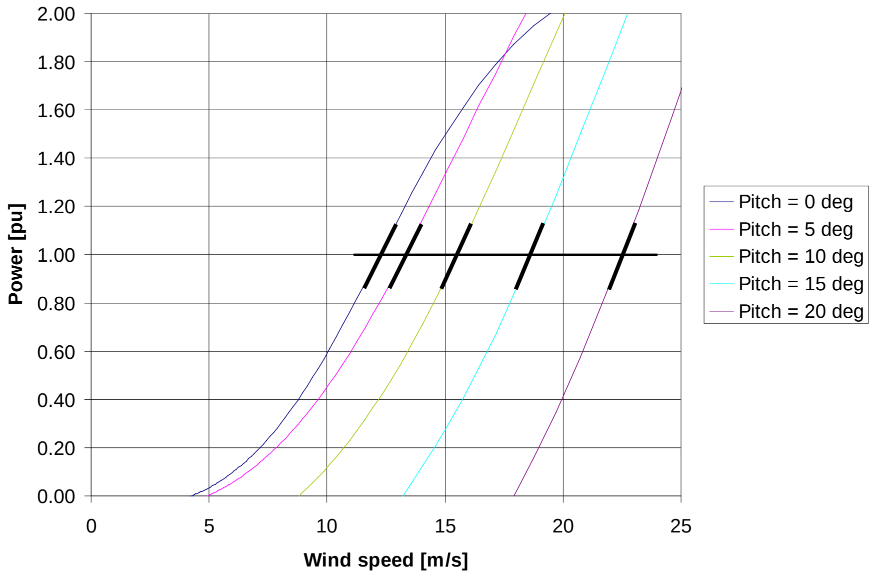


Fixed speed – active stall or pitch control

- Active (Combi) stall
- Moderate instantaneous response gradients (fixed speed no problem)
- Slow blade angle control sufficient

- Pitch control
- Large instantaneous response gradients for power limitation (variable speed desirable)
- Fast blade angle control necessary

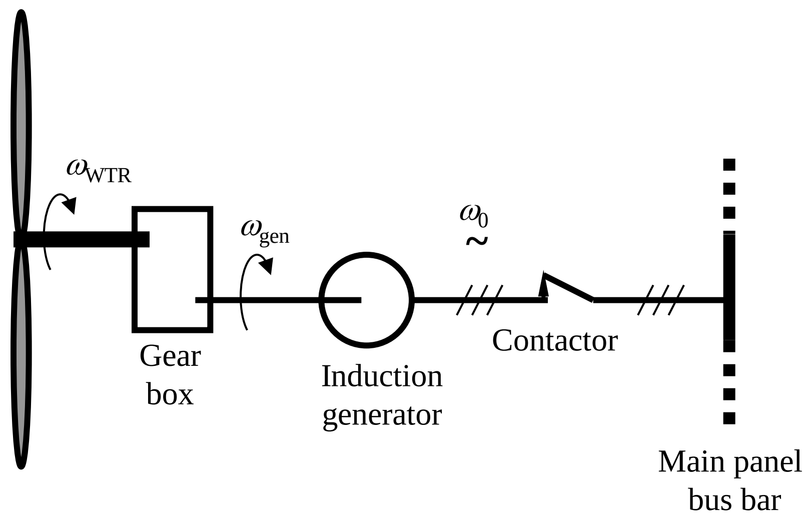




Fixed speed – directly connected induction generator

$$\omega_{\text{gen}} = g \cdot \omega_{\text{WTR}}$$

- ω_{WTR} : wind turbine rotor speed
- ω_{gen} : generator speed
- g : gear ratio



$$\omega_{\text{gen}} = \frac{1-s}{N_{\text{pp}}} \cdot \omega_0$$

- ω_0 : electric grid radial speed ($2\pi\cdot 50$ in Europe, $2\pi\cdot 60$ in USA)
- N_{pp} : number of generator pole pairs (typically 2 or 3)
- $s << 1$: generator speed almost "constant"

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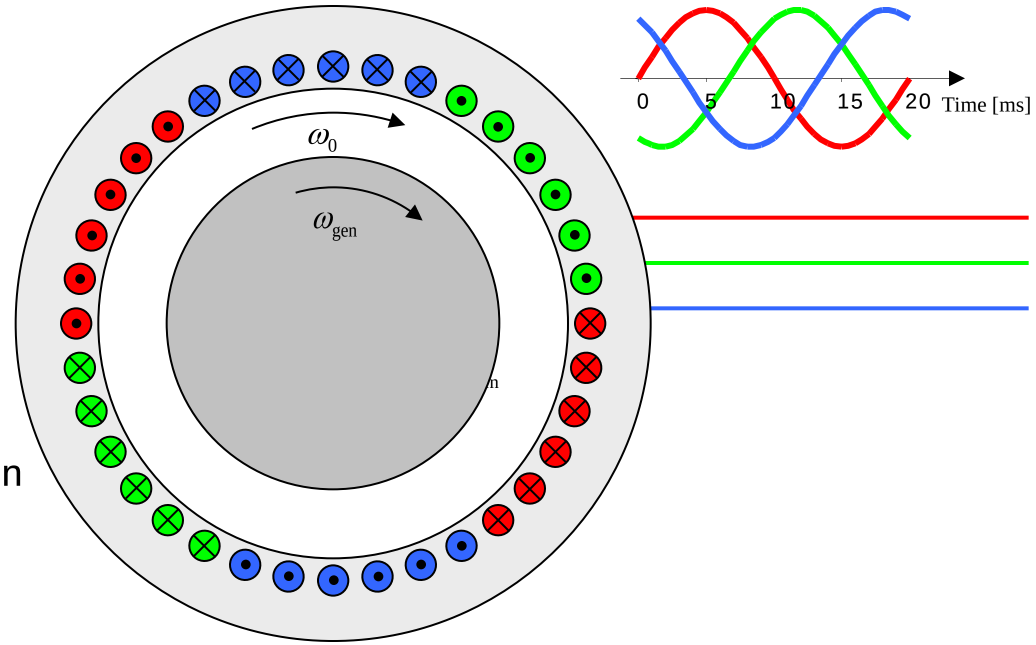


$N_{\text{pp}} = 1$

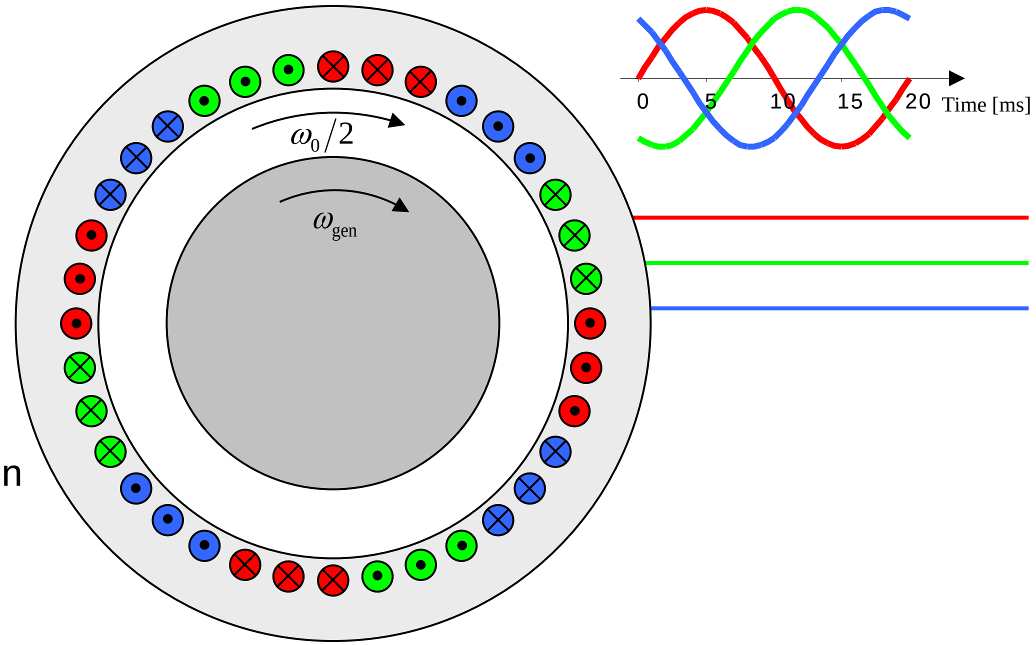
Fixed speed – directly connected induction generator

$$\omega_{\text{gen}} = g \cdot \omega_{\text{WTR}}$$

- ω_{WTR} : wind turbine rotor speed
- ω_{gen} : generator speed
- g : gear ratio

$$\omega_{\text{gen}} = \frac{1-s}{N_{\text{pp}}} \cdot \omega_0$$

- ω_0 : electric grid radial speed ($2\pi \cdot 50$ in Europe, $2\pi \cdot 60$ in USA)
- N_{pp} : number of generator pole pairs (typically 2 or 3)
- $s << 1$: generator speed almost "constant"

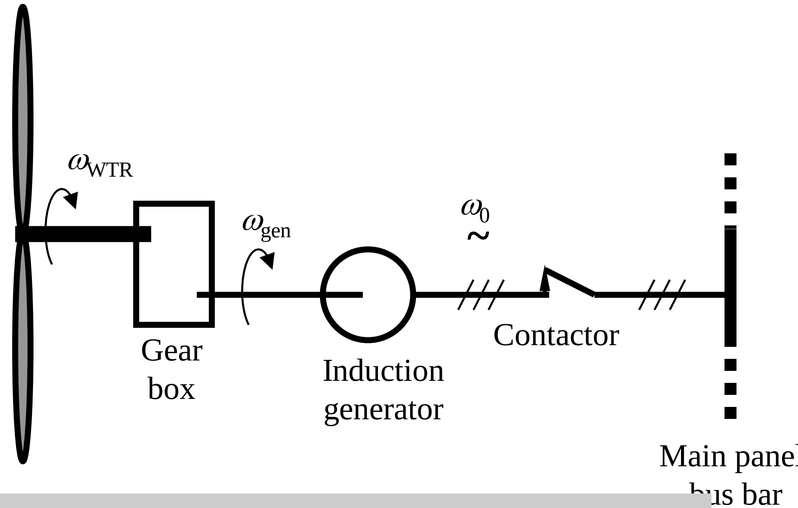


$N_{\text{pp}} = 2$

Fixed speed – directly connected induction generator

$$\omega_{\text{gen}} = g \cdot \omega_{\text{WTR}}$$

- ω_{WTR} : generator speed
- ω_{gen} : generator speed
- g : gear ratio



$$\omega_{\text{gen}} = \frac{1-s}{N_{\text{pp}}} \cdot \omega_0$$

- ω_0 : electric grid radial speed ($2\pi \cdot 50$ in Europe, $2\pi \cdot 60$ in USA)
- N_{pp} : number of generator pole pairs (typically 2 or 3)
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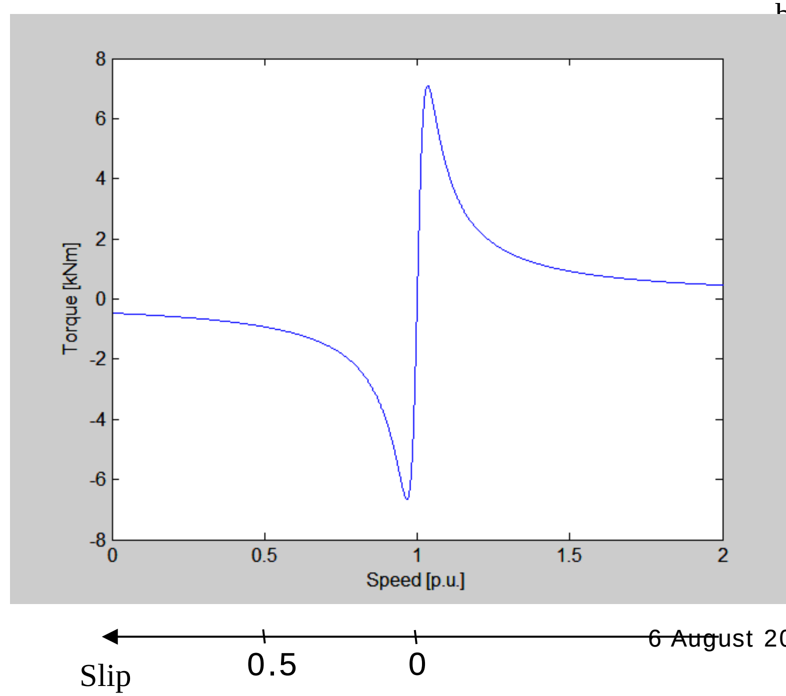


Fixed speed continuous operation - summary

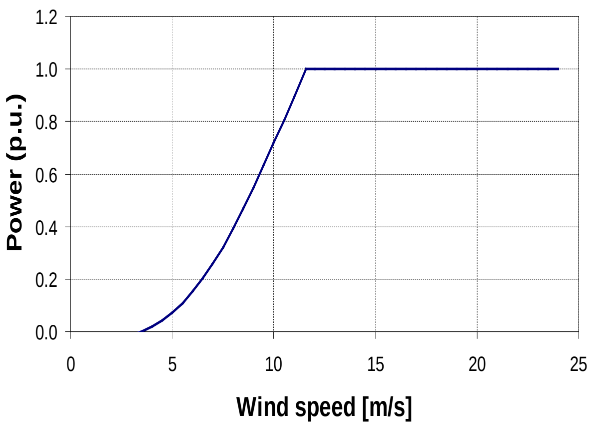
- Wind turbines with directly connected induction generators are speed controlled by the generator torque, which is approximately proportional to the slip (slip is difference between grid synchronous rotor speed and actual generator rotor speed).
- The generator can be “geared” by increasing the number of pole pairs
- Fixed speed turbines can control the speed by changing the number of pole pairs, typically between 2 and 3, depending on the wind speed.

Exercise 1: fixed speed

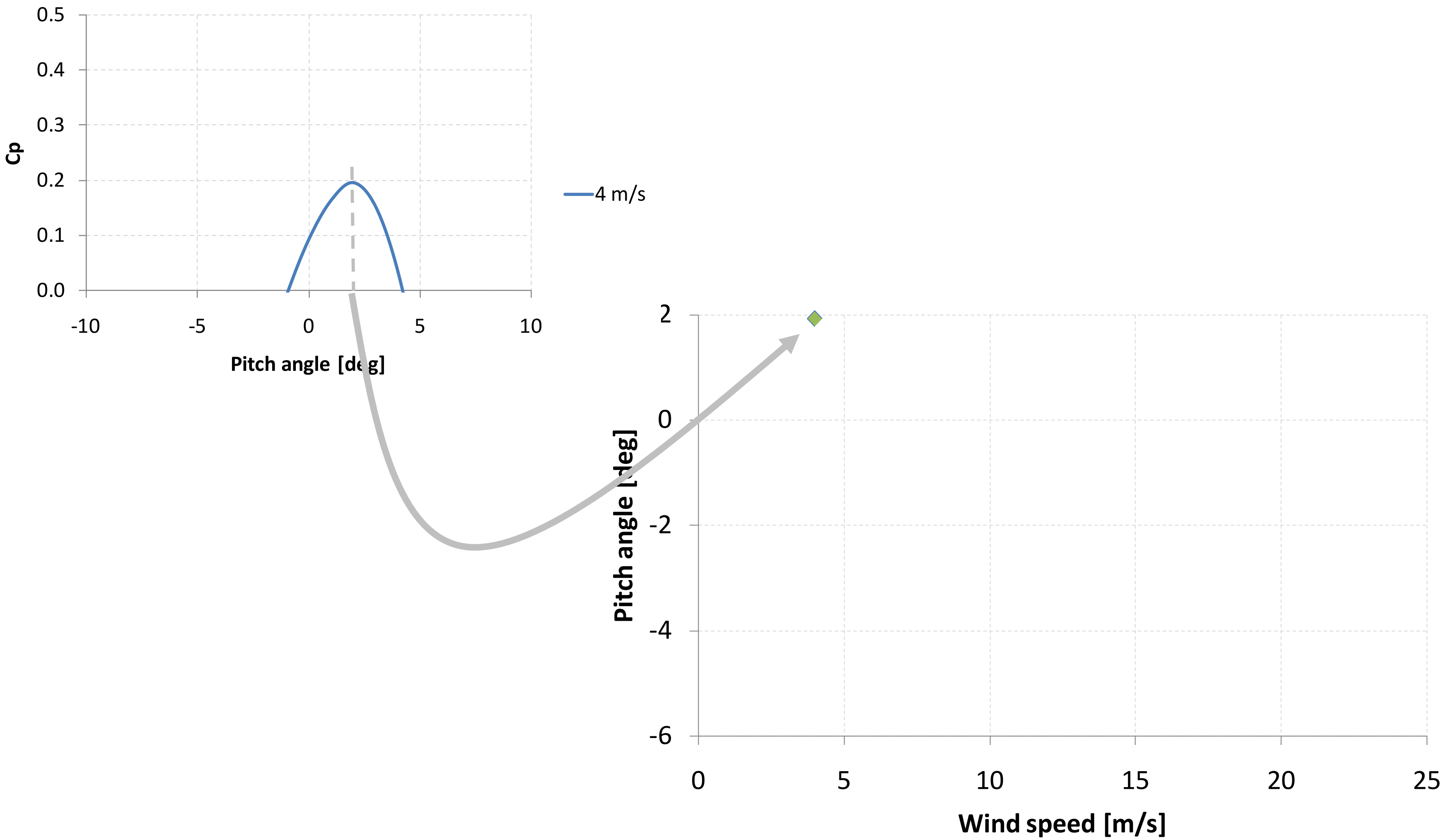
- Open excel sheet with C_p data
- A fixed speed wind turbine with the C_p data in table has rotor diameter 40 m, tip speed 70 m/s. Make the power curve if the pitch angle is 0 deg.
- At which pitch angle (integer degree) should the blades be mounted to the hub to obtain the maximum power 600 kW? Hint: try to increase the pitch angle negatively step by step and observe the power curve until you get the desired maximum.
- The turbine uses $N_{pp}=2$ coupling of generator windings for high wind speeds and $N_{pp}=3$ for low wind speeds. What is the tip speed for low wind speeds?
- The turbine is passive stall controlled. Show the power curve for low wind speeds and high wind speeds, and identify the wind speed at which switching between generator speeds is feasible.

Active Stall example

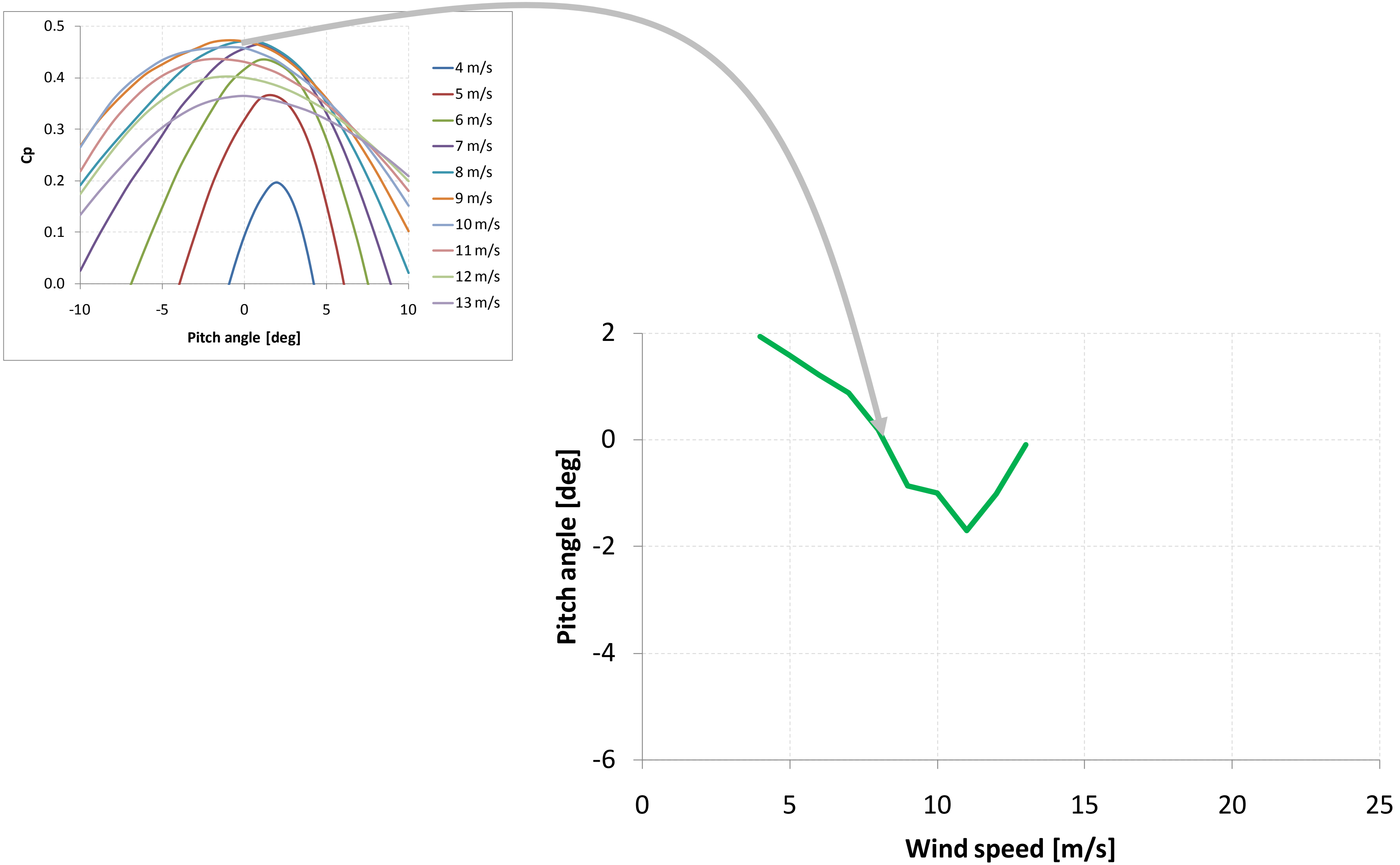
- General operation modes active stall
  - Power optimisation (lookup table)
  - Power limitation (closed loop power control)
    - Normal operation (averaged power, sample & hold)
    - Overpower protection (instant. power, continuous pitching)
  - Transition between optimisation and limitation



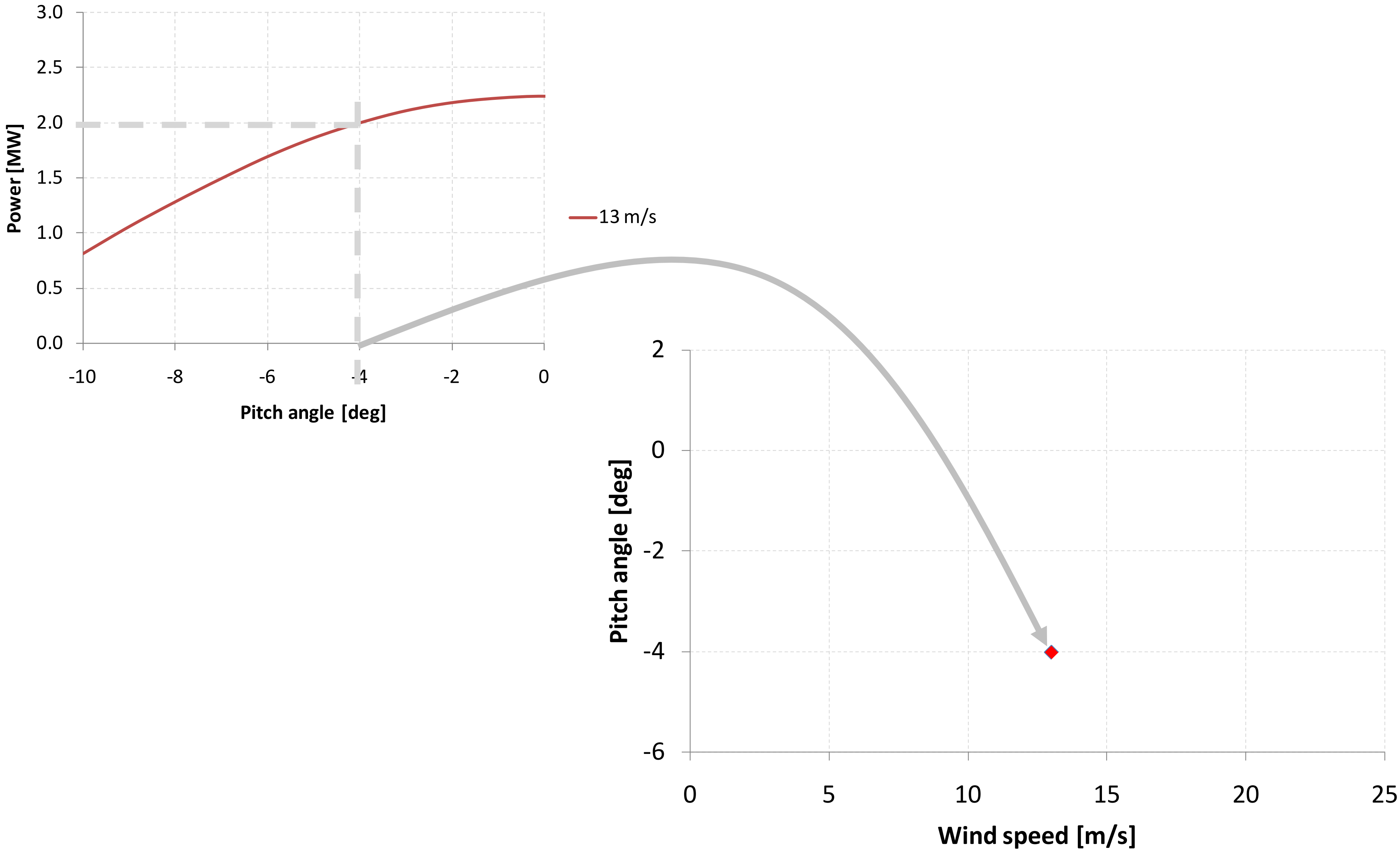
Power Optimisation



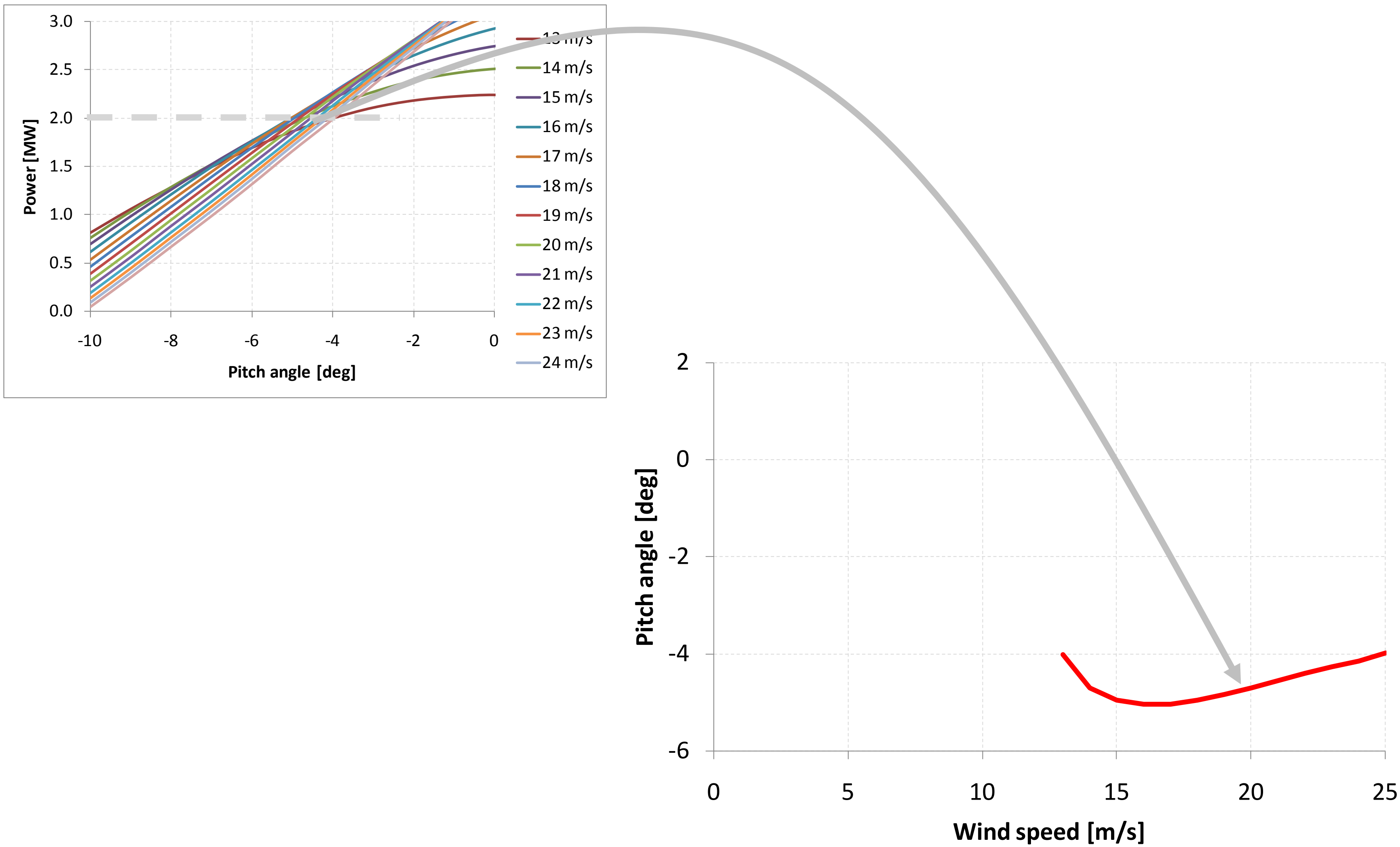
Power Optimisation



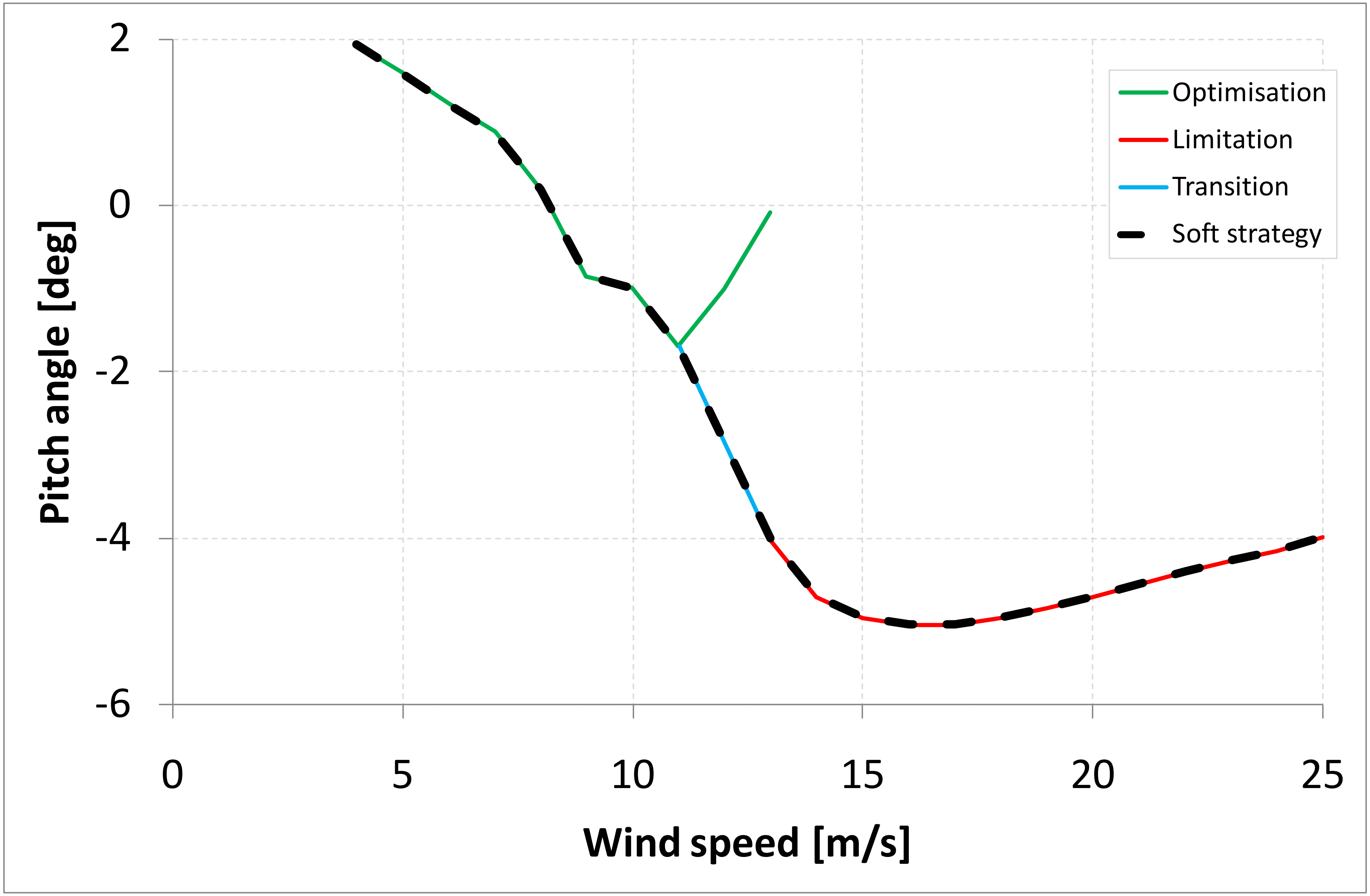
Power Limitation



Power Limitation

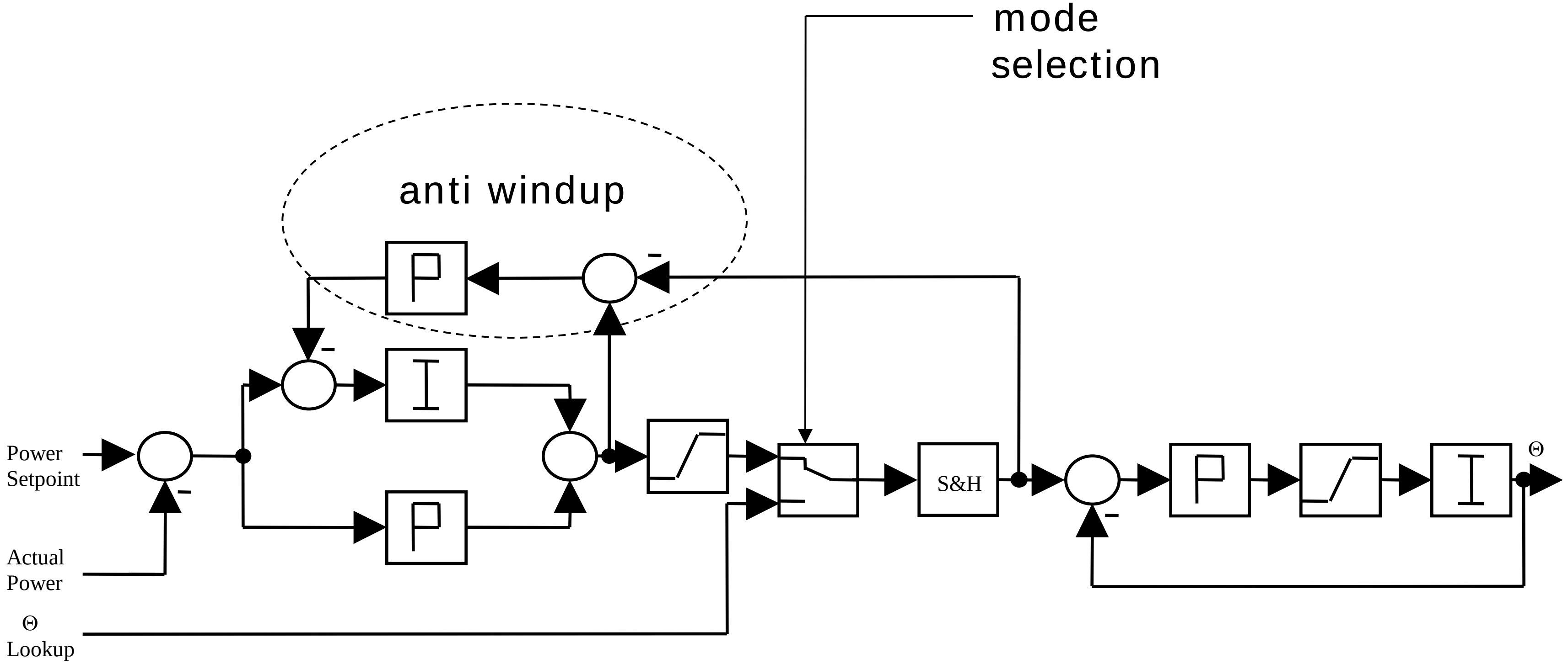


Transision

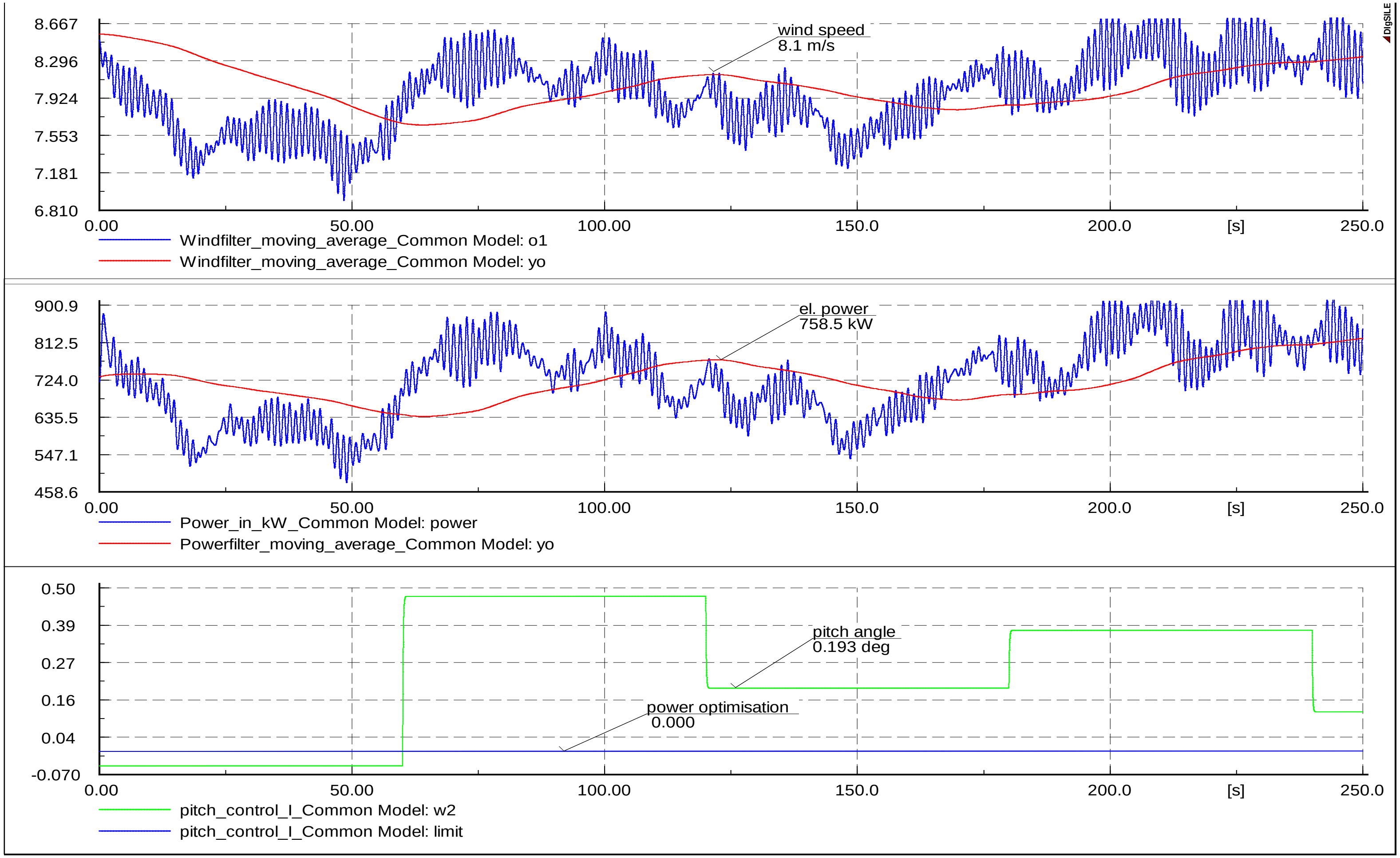


2
0
-2
-4
-6
0
5
10
15
20
25
Pitch angle [deg]
Wind speed [m/s]
Optimisation
Limitation
Transition
Soft strategy

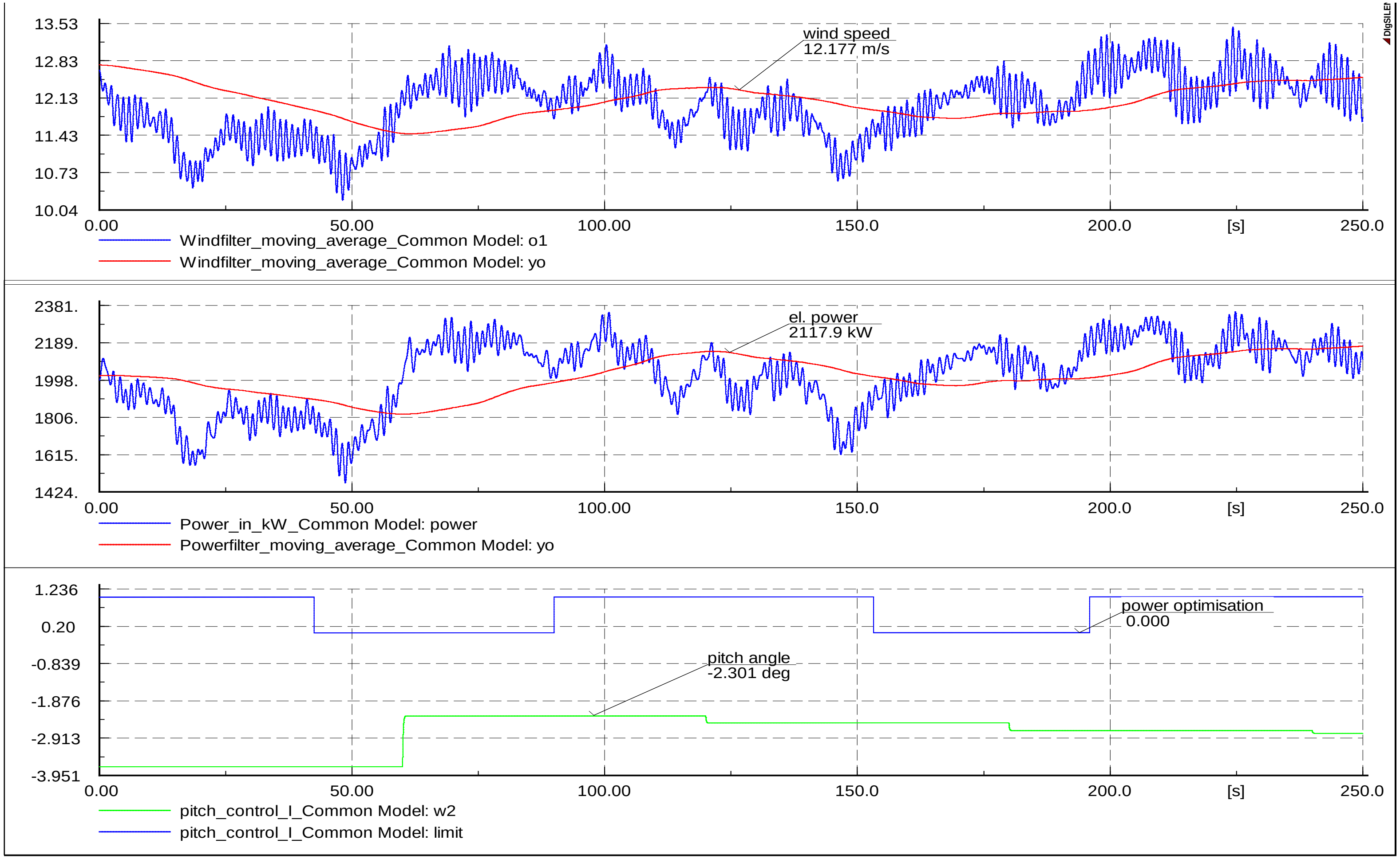
Control Circuit



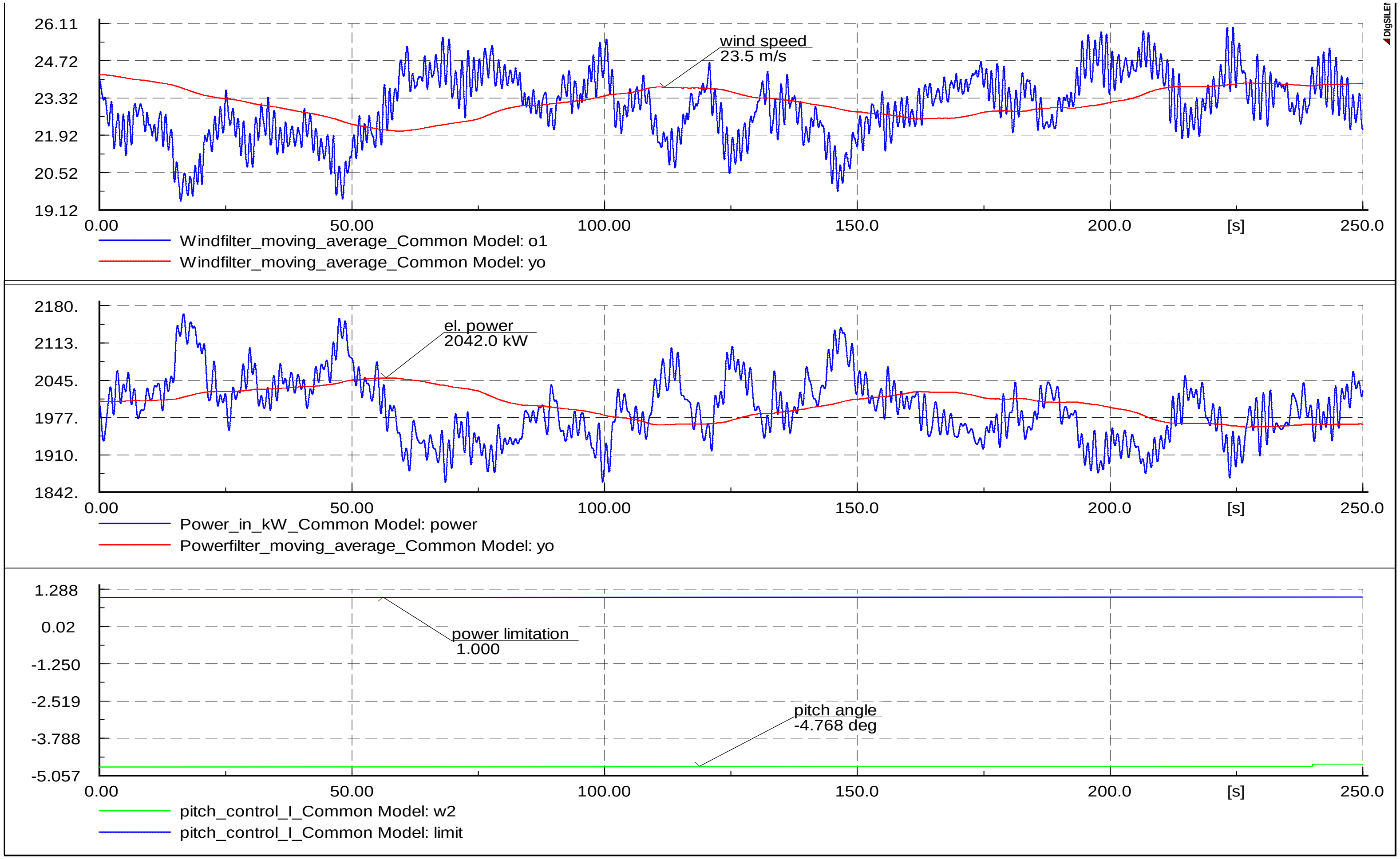
Simulation Power Optimisation



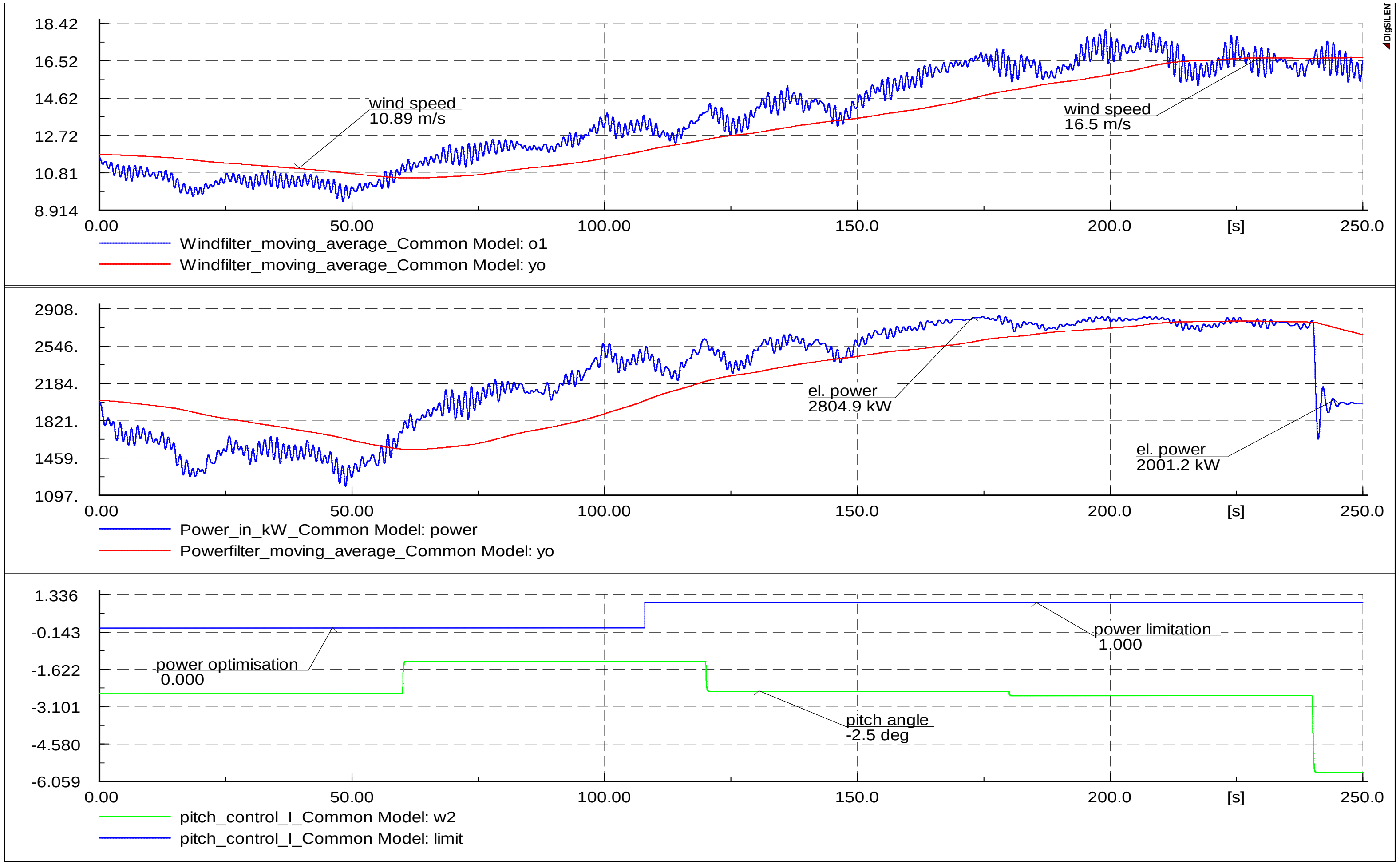
Simulation Transition



Simulation Power Limitation



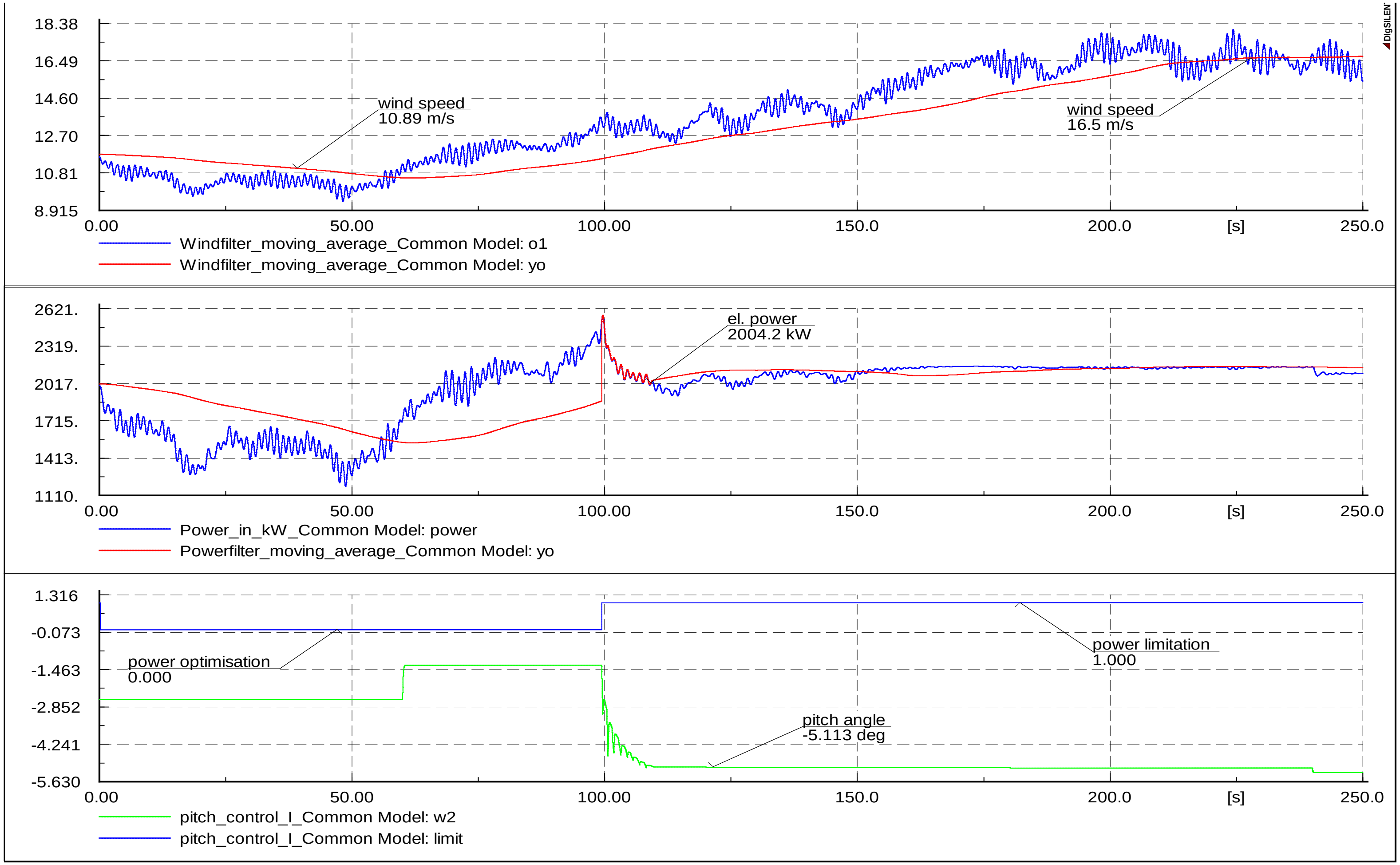
Simulation Overpower



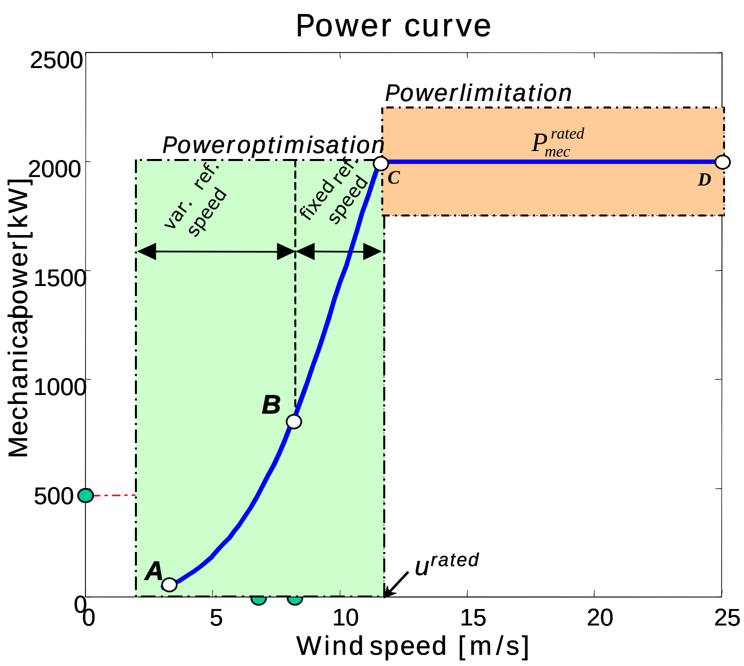
Overpower Protection

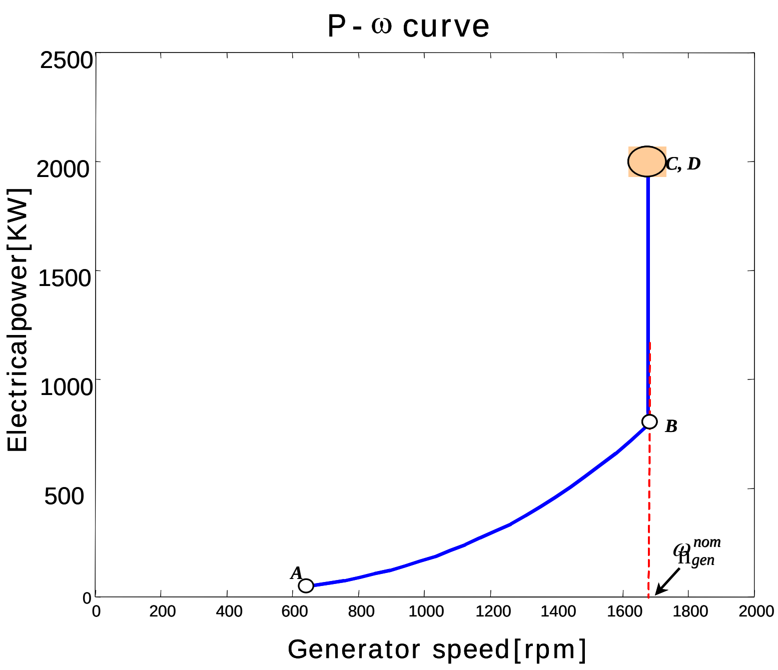
- Function of overpower protection
  - Disable sample and hold
    - (continuous controller action possible)
  - Instantaneous power signal for power controller
    - (controller uses instantaneous power instead of averaged power)
  - Overpower protection active for fixed period of time

Simulation Overpower Protection



Variable speed control strategy – continuous operation

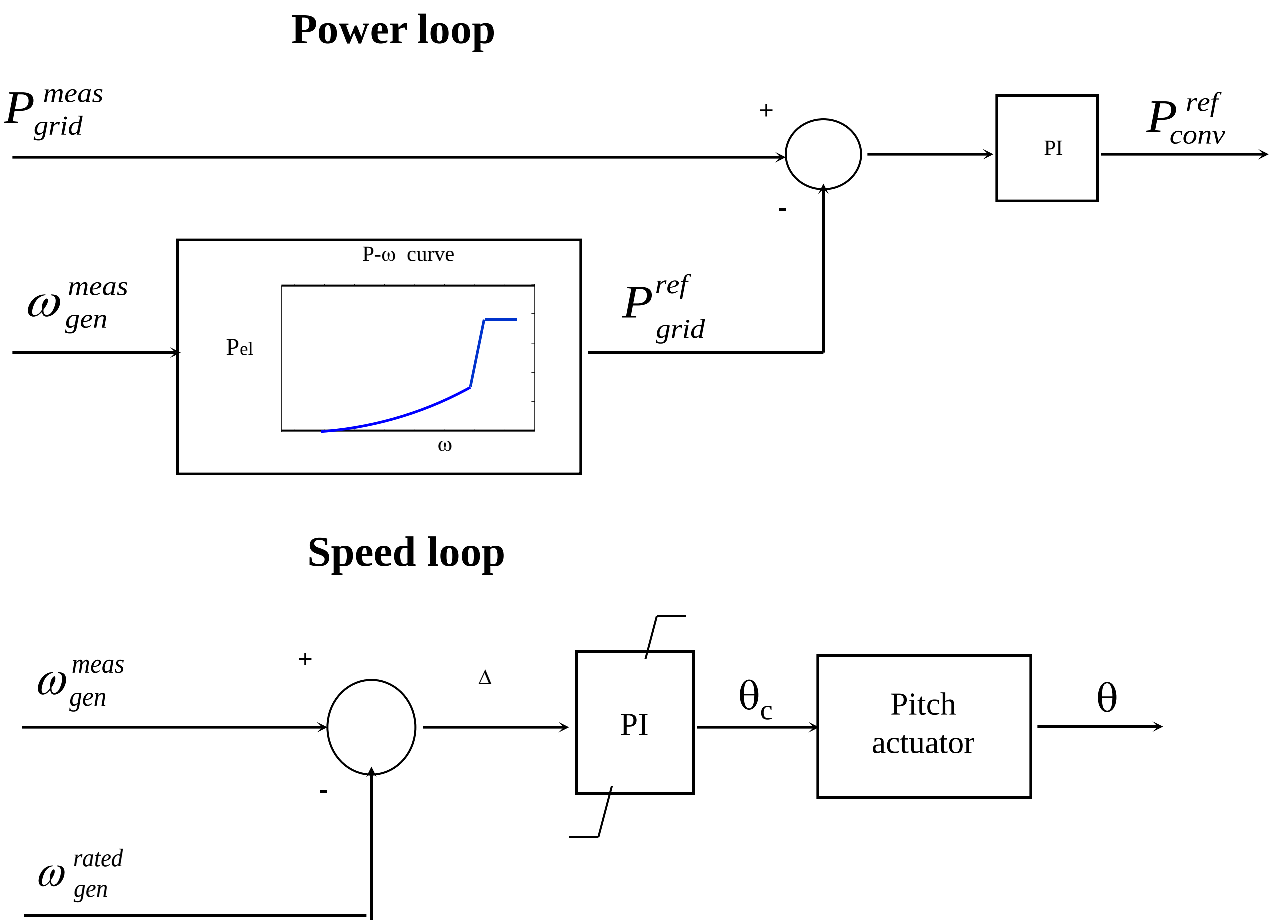




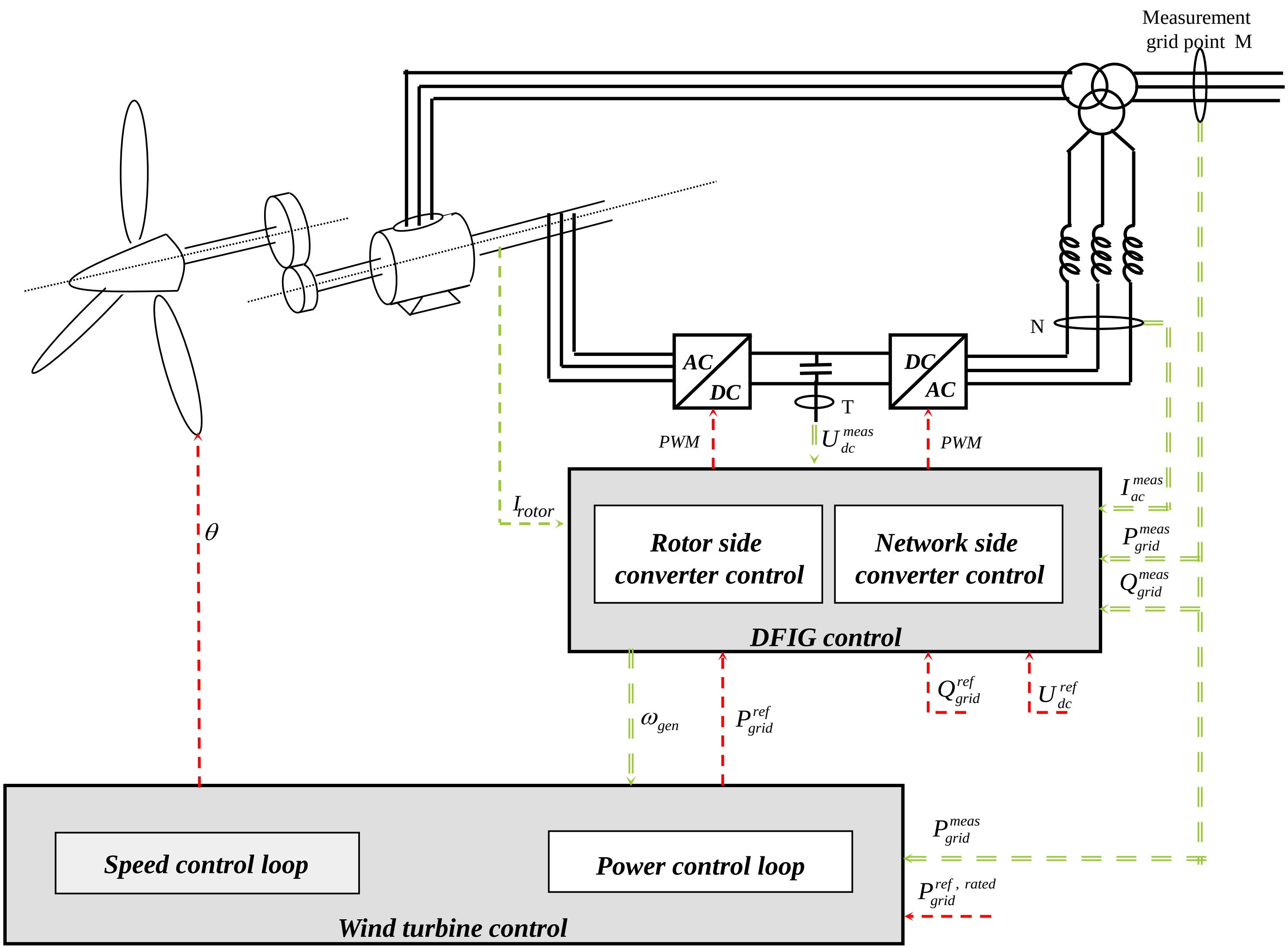
Exercise 2 – variable speed

- The Cp data is used for a variable speed / pitch controlled wind turbine with rotor diameter 80 m. Specify equation for power curve in optimisation region A-B
- Specify the corresponding relation between wind turbine rotor speed and power
- The generator is a doubly fed induction generator with two pole pairs ($N_{pp}=2$). The generator speed at rated wind speed is 1650 rpm (i.e. the maximum generator speed). The rated grid frequency is 50 Hz. Find the generator slip corresponding to rated wind speed.
- The rated rotor tip speed (rotor speed at rated wind speed) is 70 m/s. Find the gear ratio.
- Specify the relation between generator speed and power in region A-B
- Specify the relation between generator speed and torque in region A-B

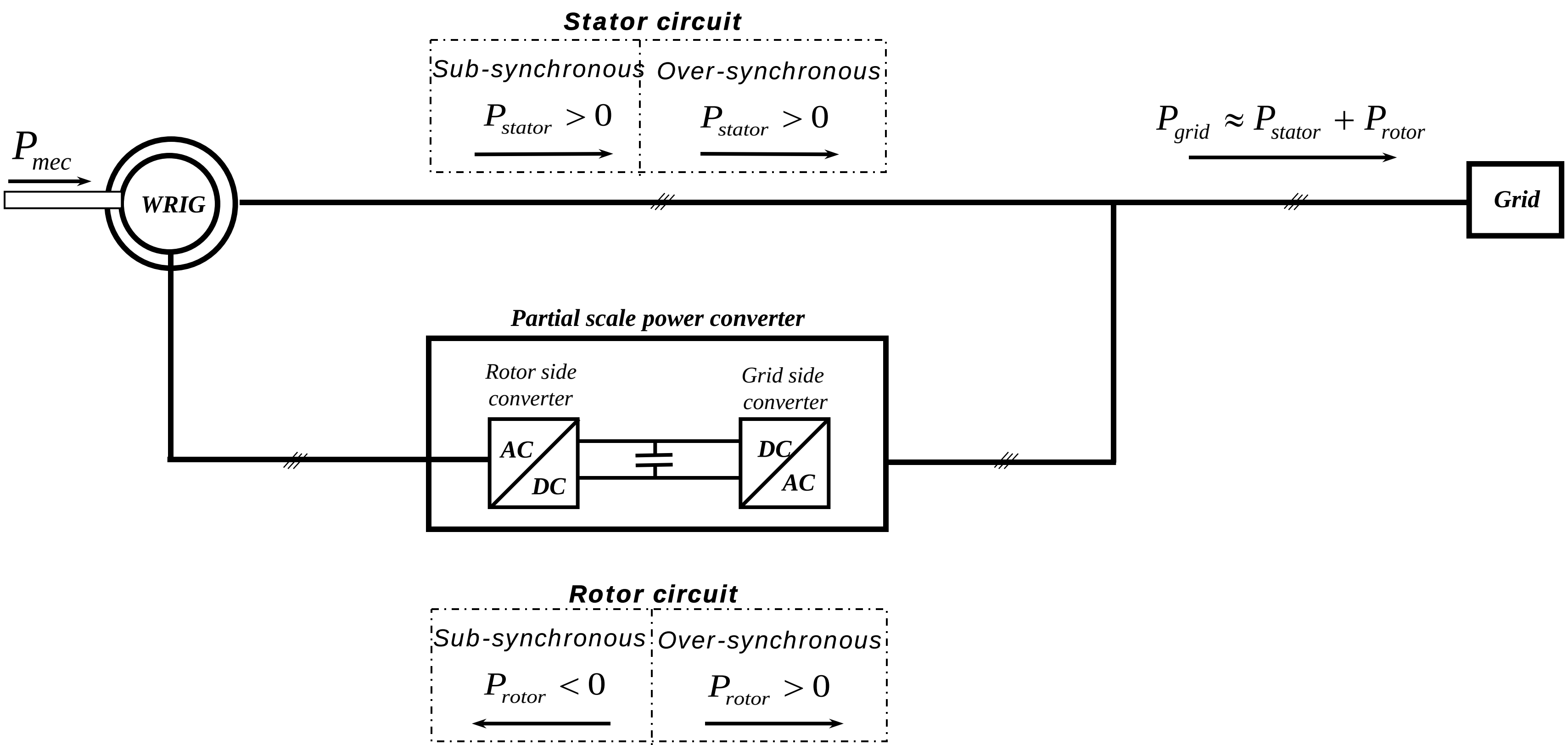
Variable speed control loops



Doubly fed generator (DFG)

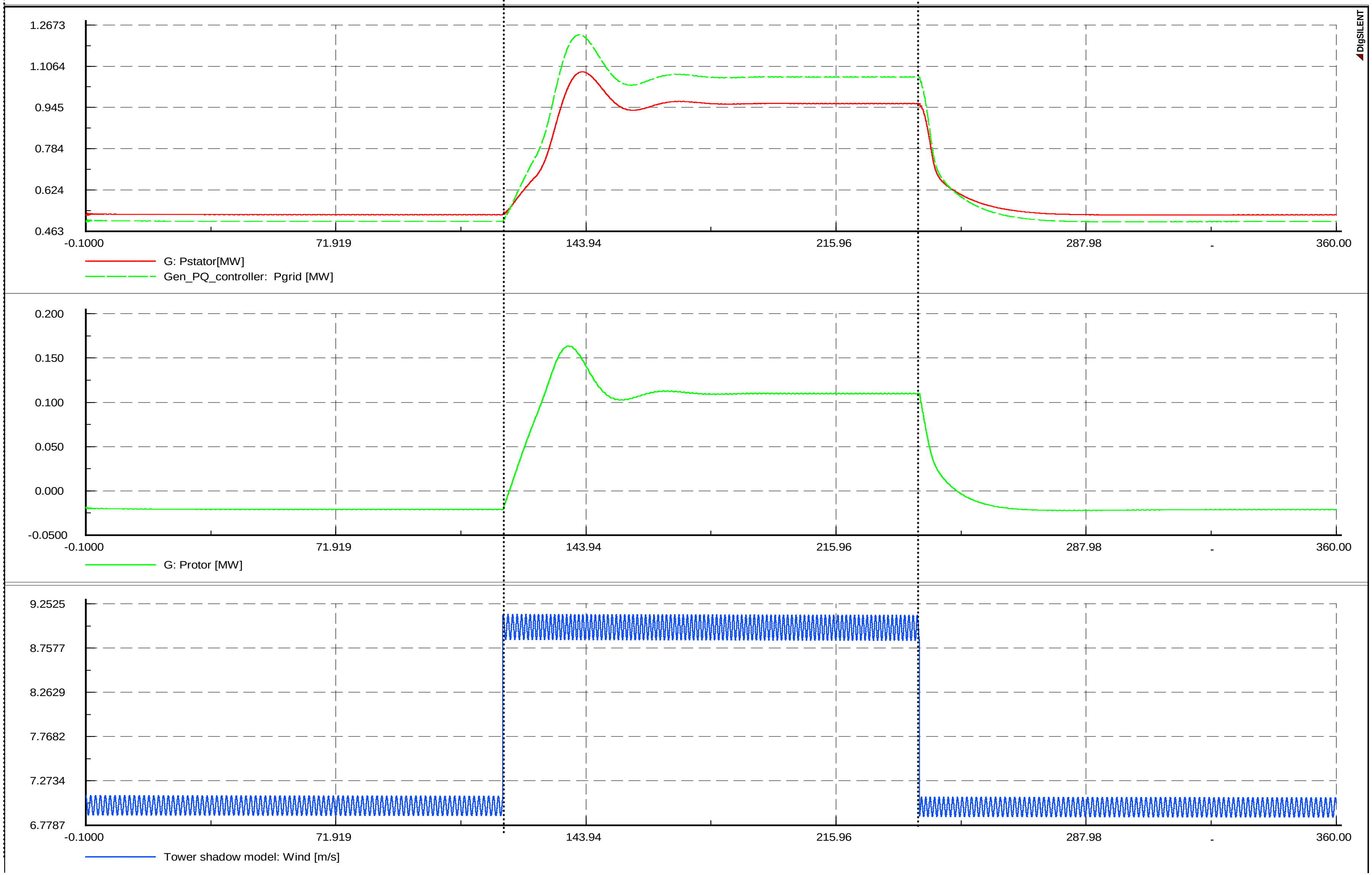


Doubly fed generator – power flow vs. rotor speed

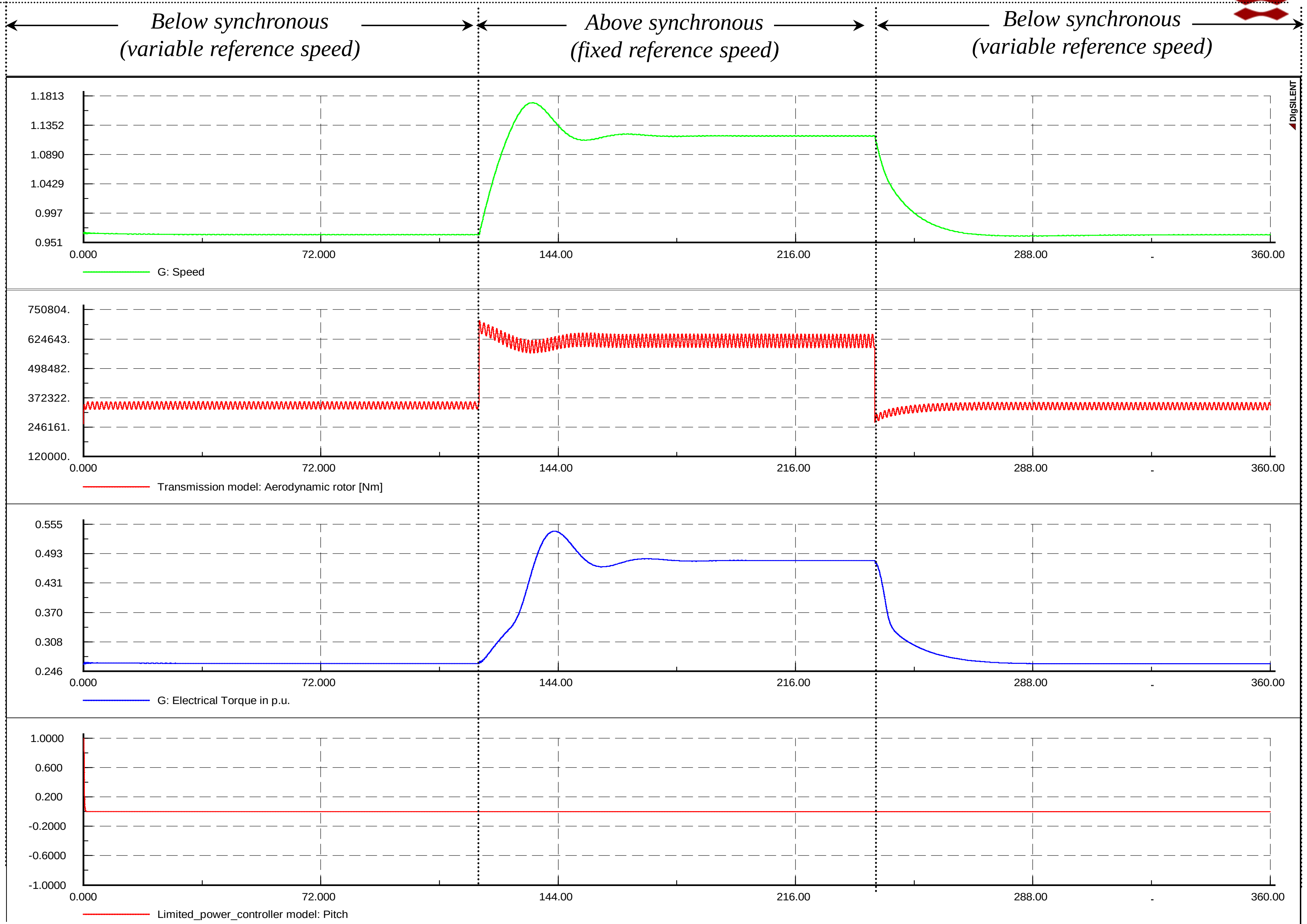


Simulation – optimal power control (AB)

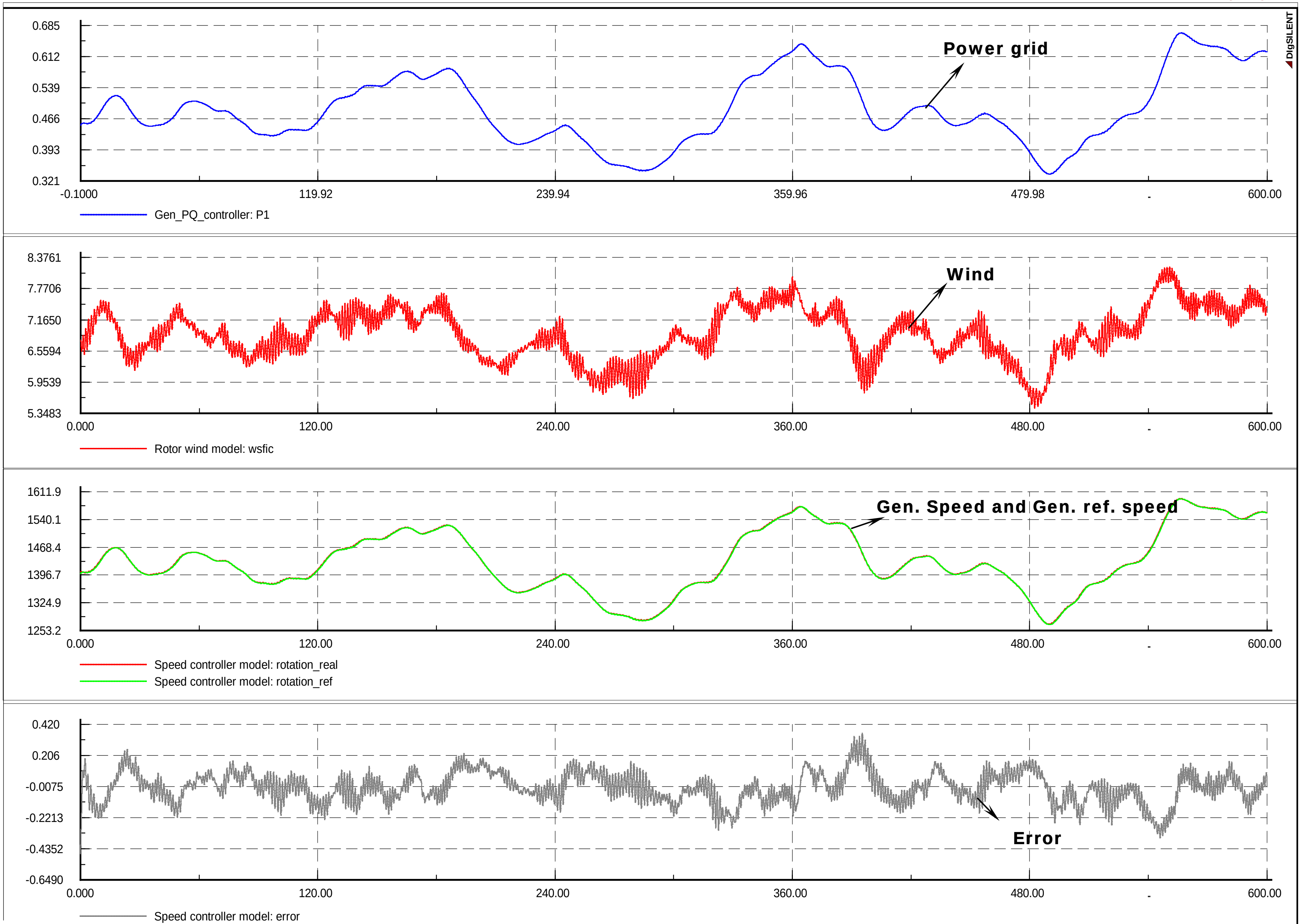
Below synchronous (variable reference speed) | Above synchronous (fixed reference speed) | Below synchronous (variable reference speed)



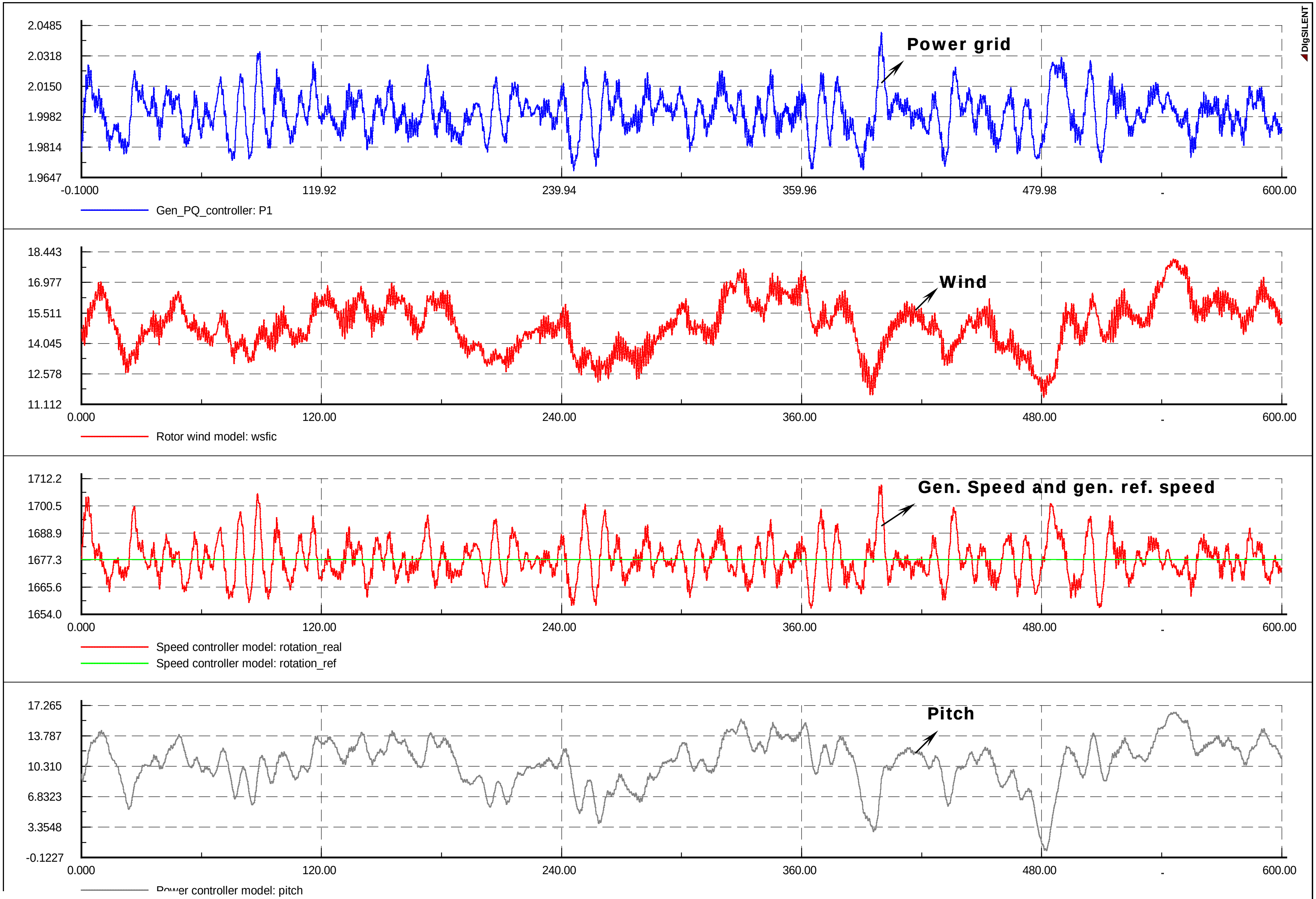
Simulation – optimal power control (AB)



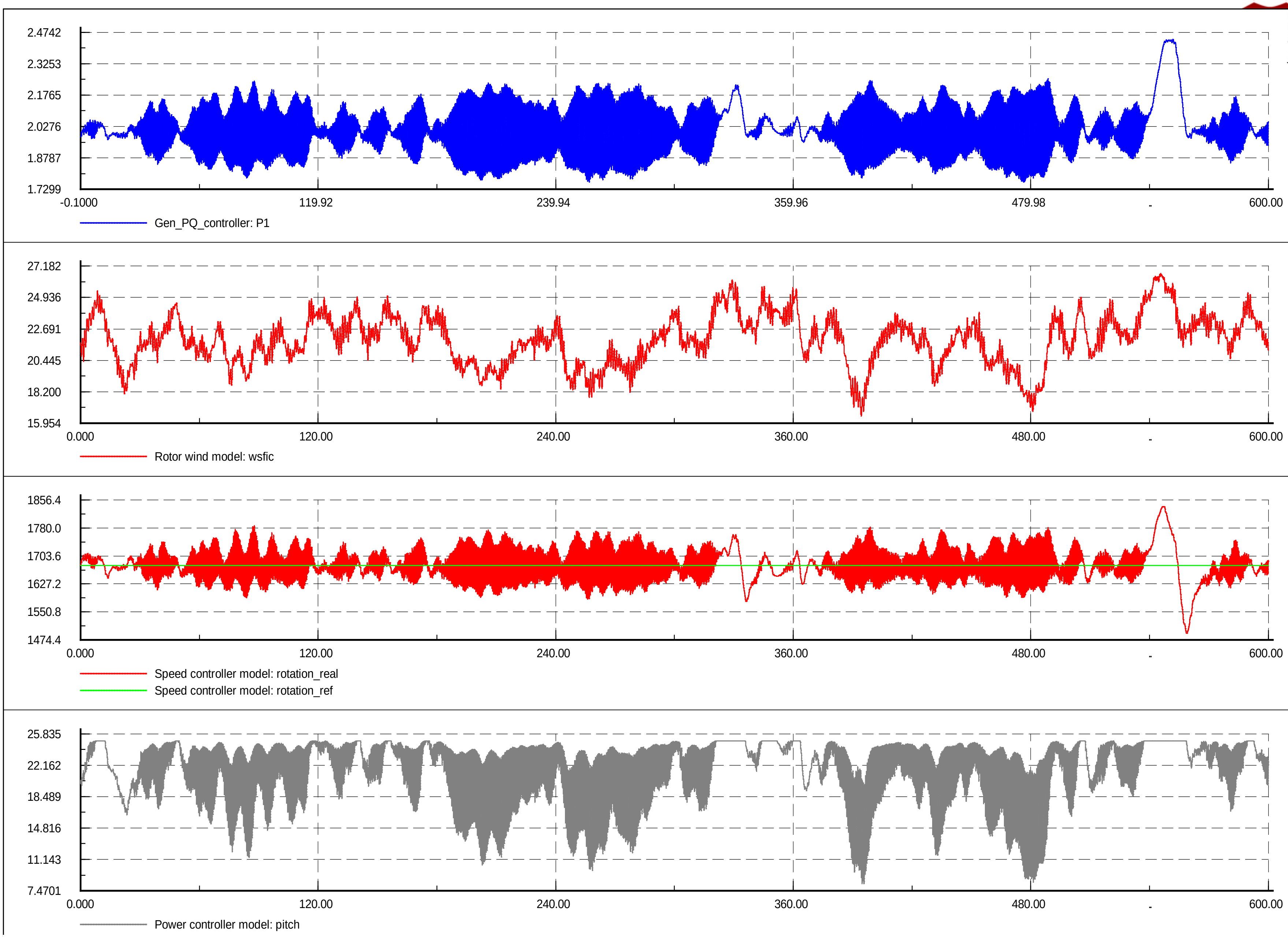
Simulation - wind 7m/s – optimisation



Simulation - wind 15 m/s



Simulation - wind 22 m/s

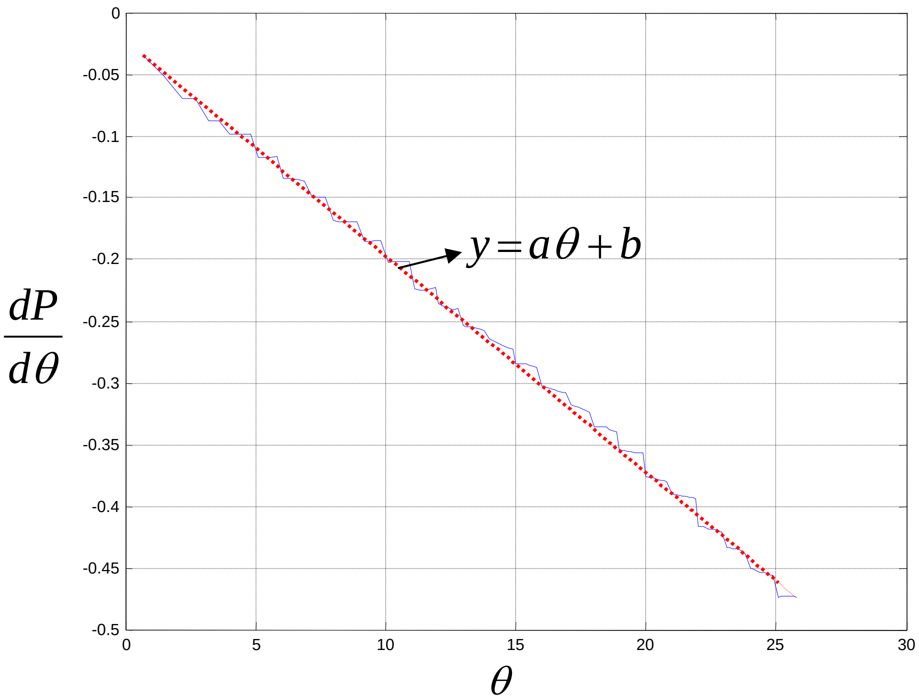


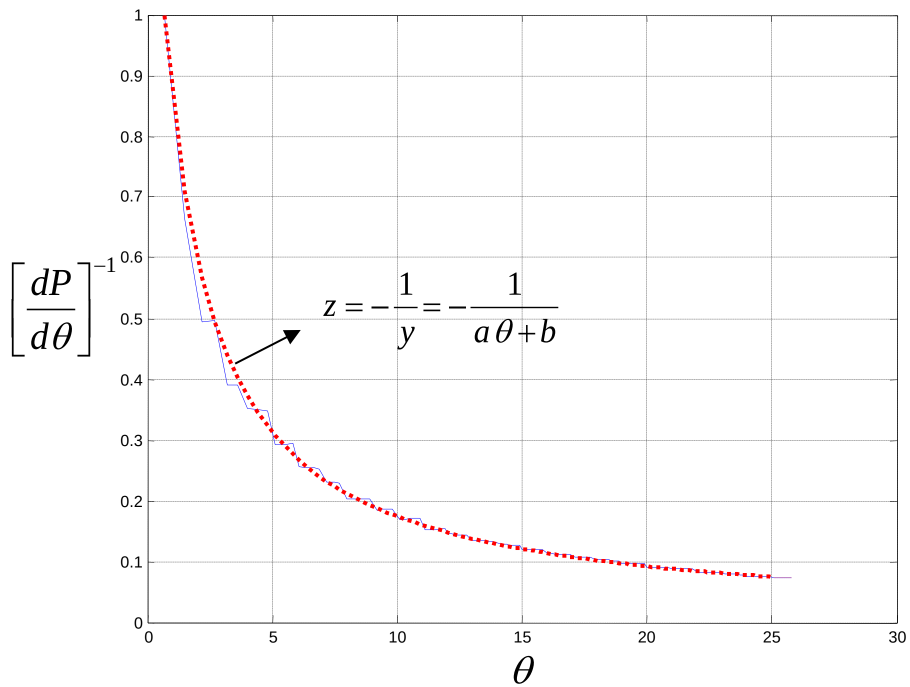
Gain scheduling

$$K_{system} = K_{PI} \left[\frac{dP}{d\theta}\right]$$

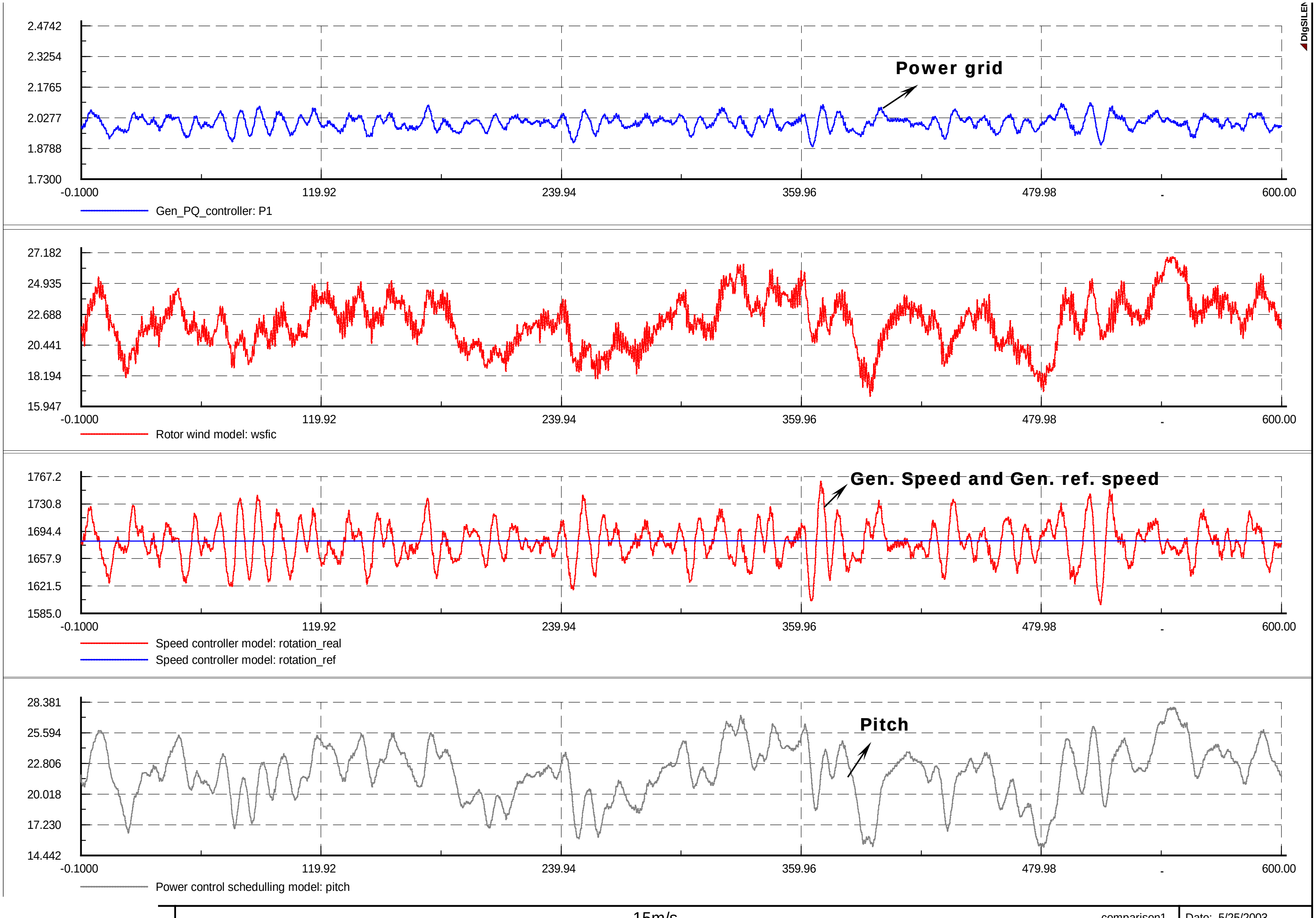
$$K_{PI} = K_{pitch}$$

$$K_{PI} = K_{pitch} \left[\frac{dP}{d\theta}\right]^{-1}$$



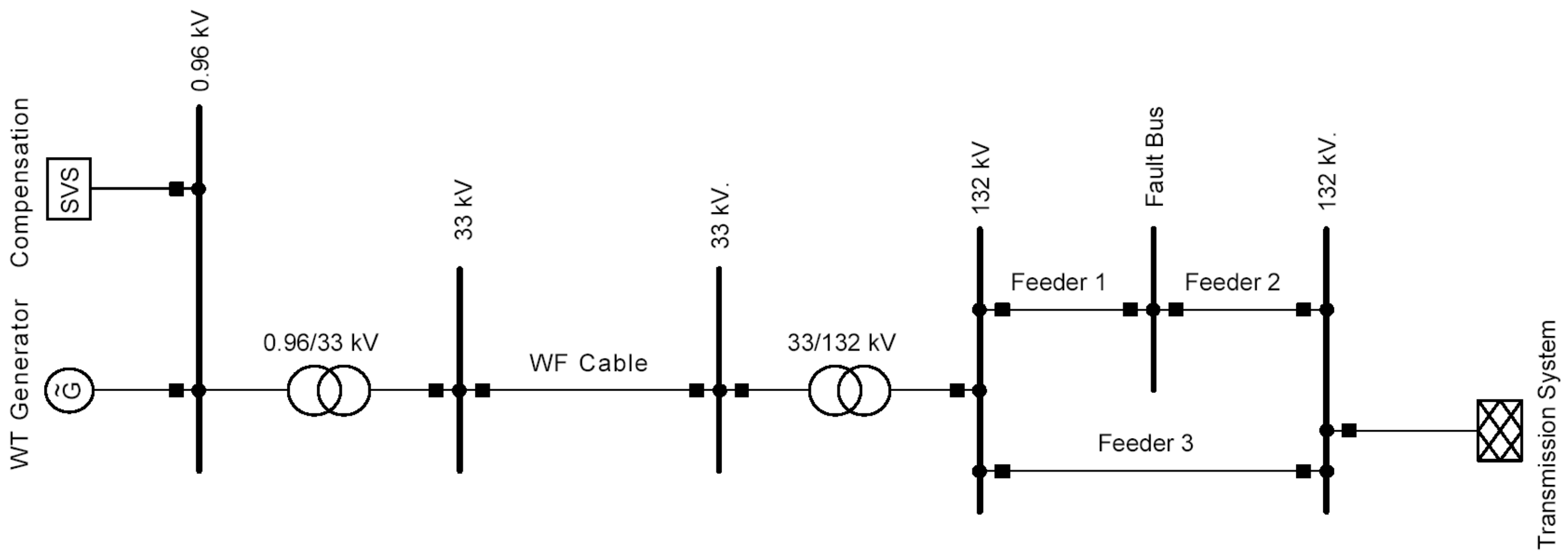


Simulation - wind 22 m/s – gain schedulling

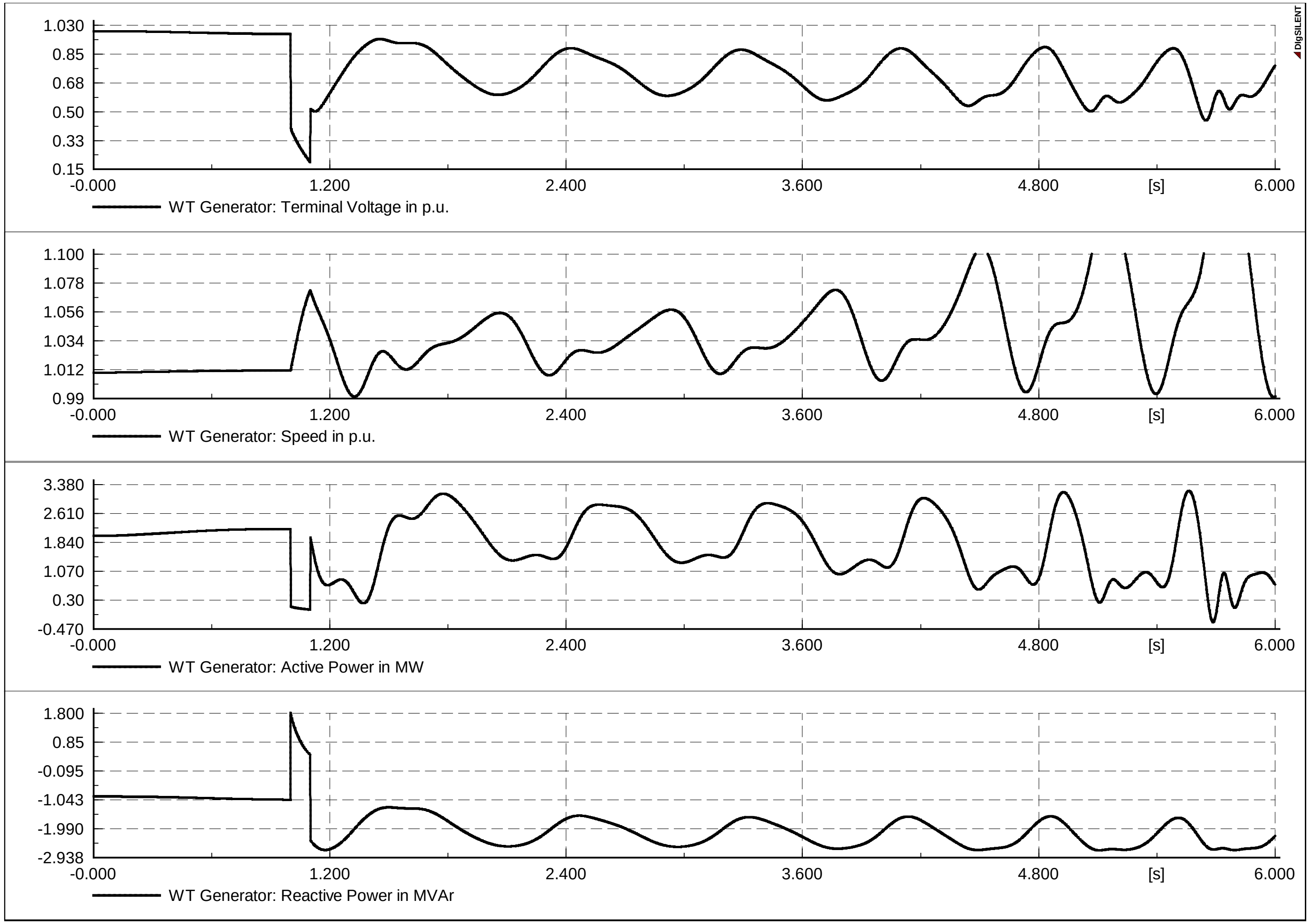


Fault-ride-through control

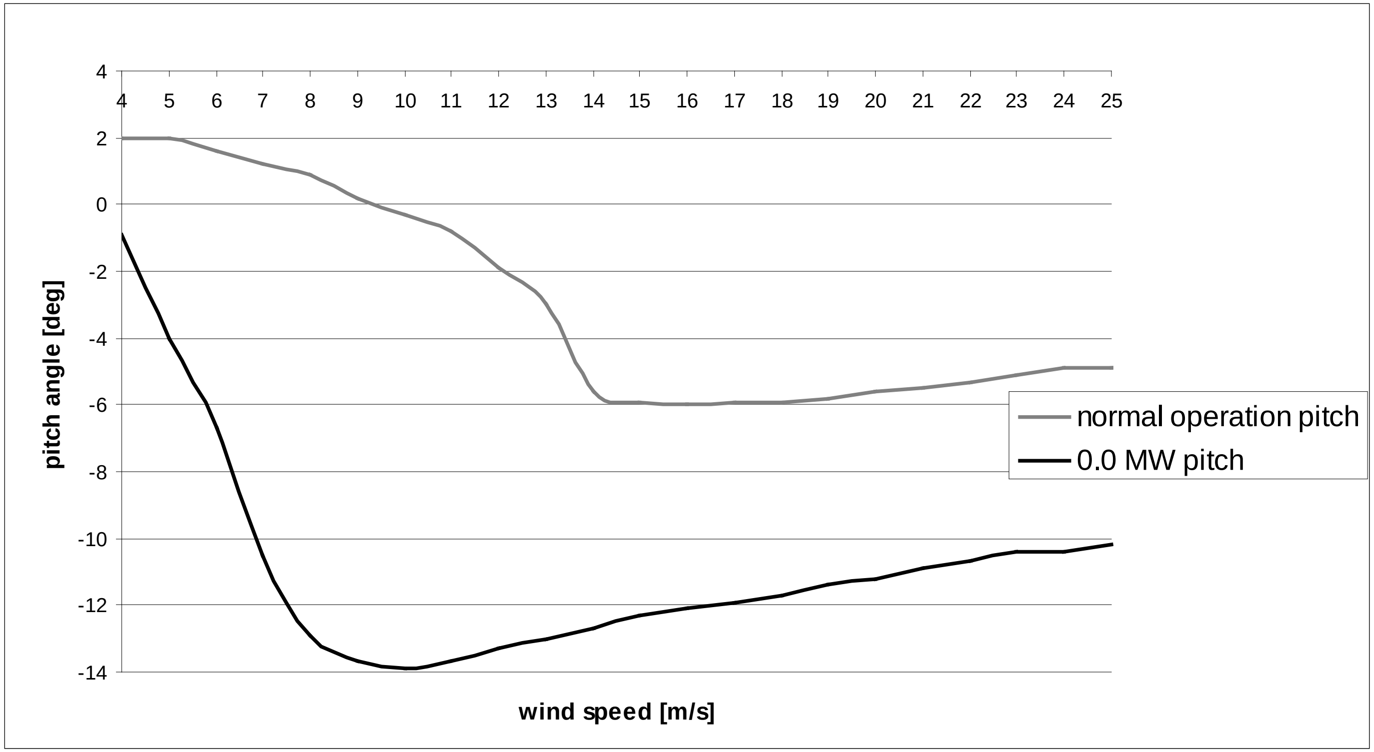
- Example active stall
  - short circuit at “Fault Bus”
  - isolation of fault



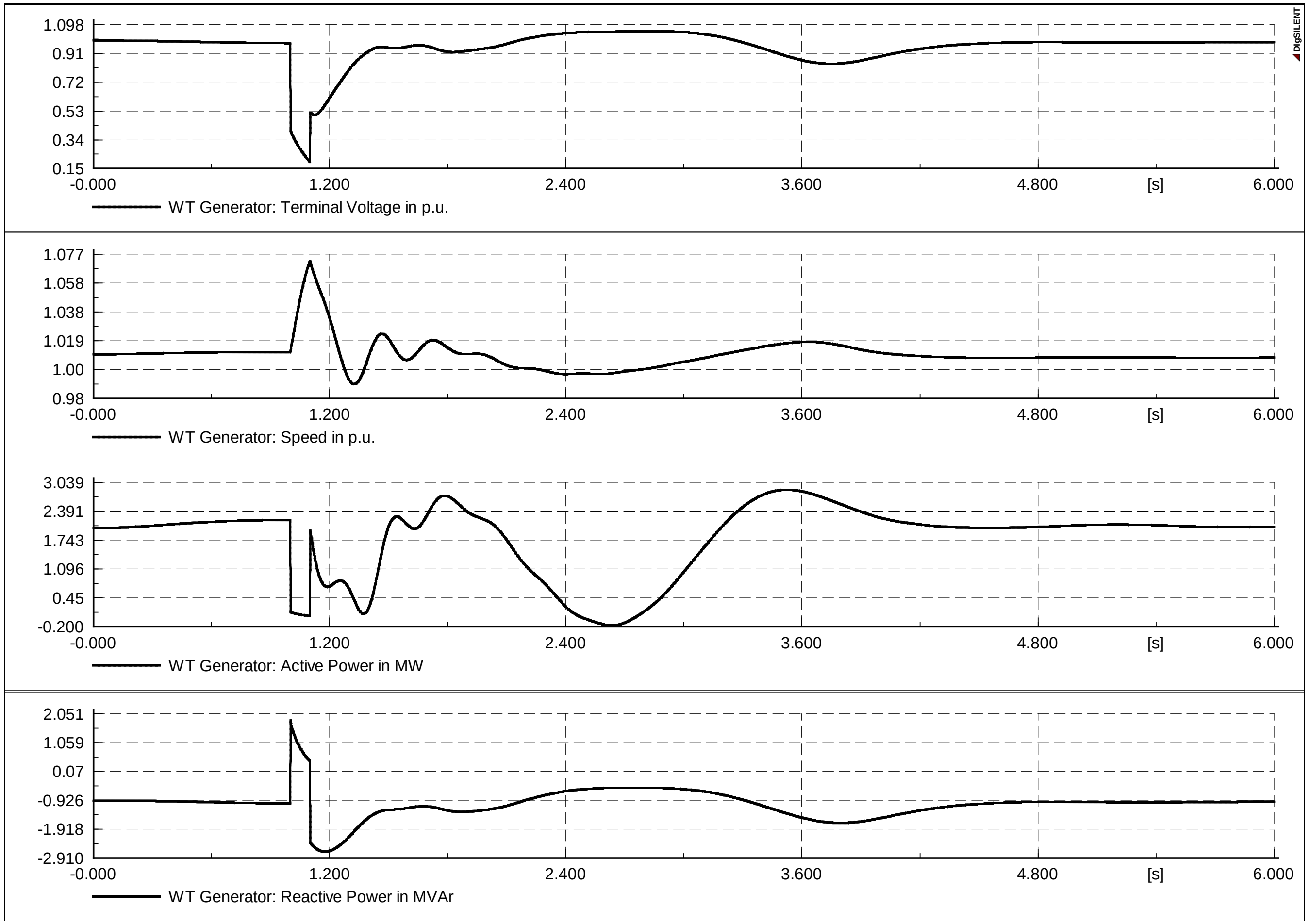
No fault-ride-through control



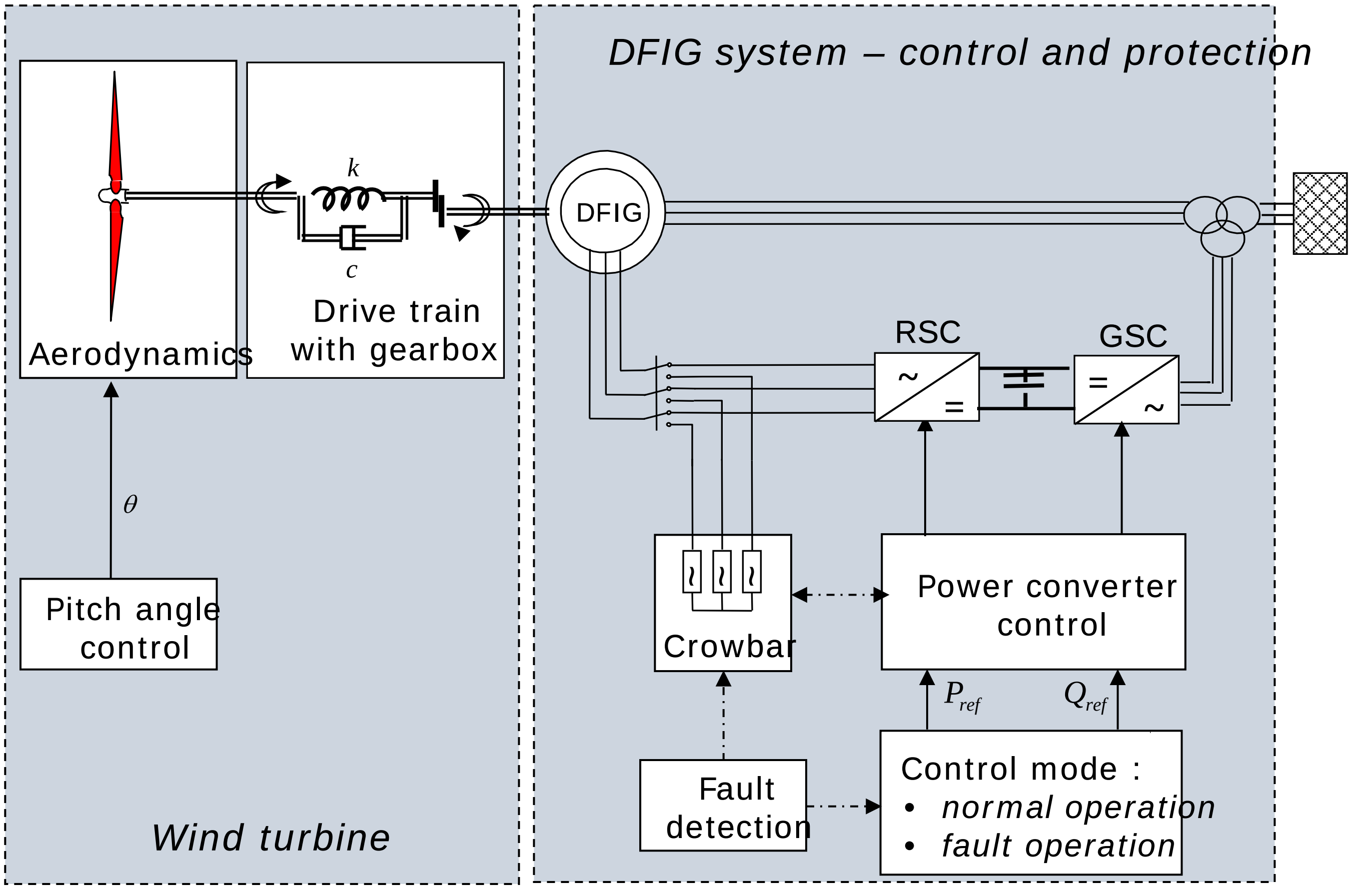
Simple fault-ride-thorugh control: fast pitch to zero-power



Short circuit simulated with fault-ride-through control

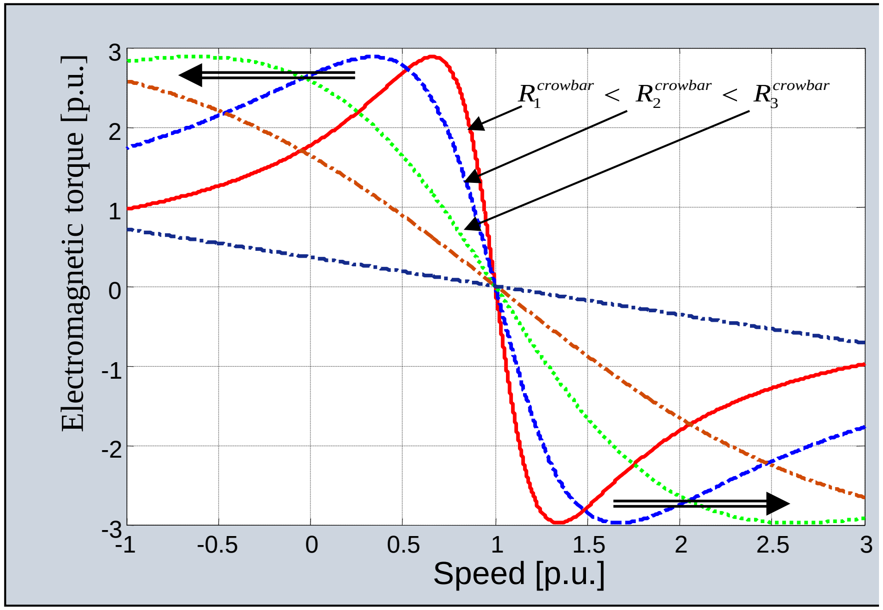


Fault ride through – DFG with crowbar



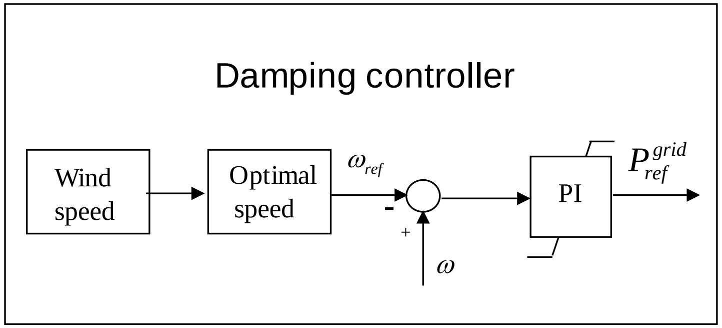
Crowbar effects

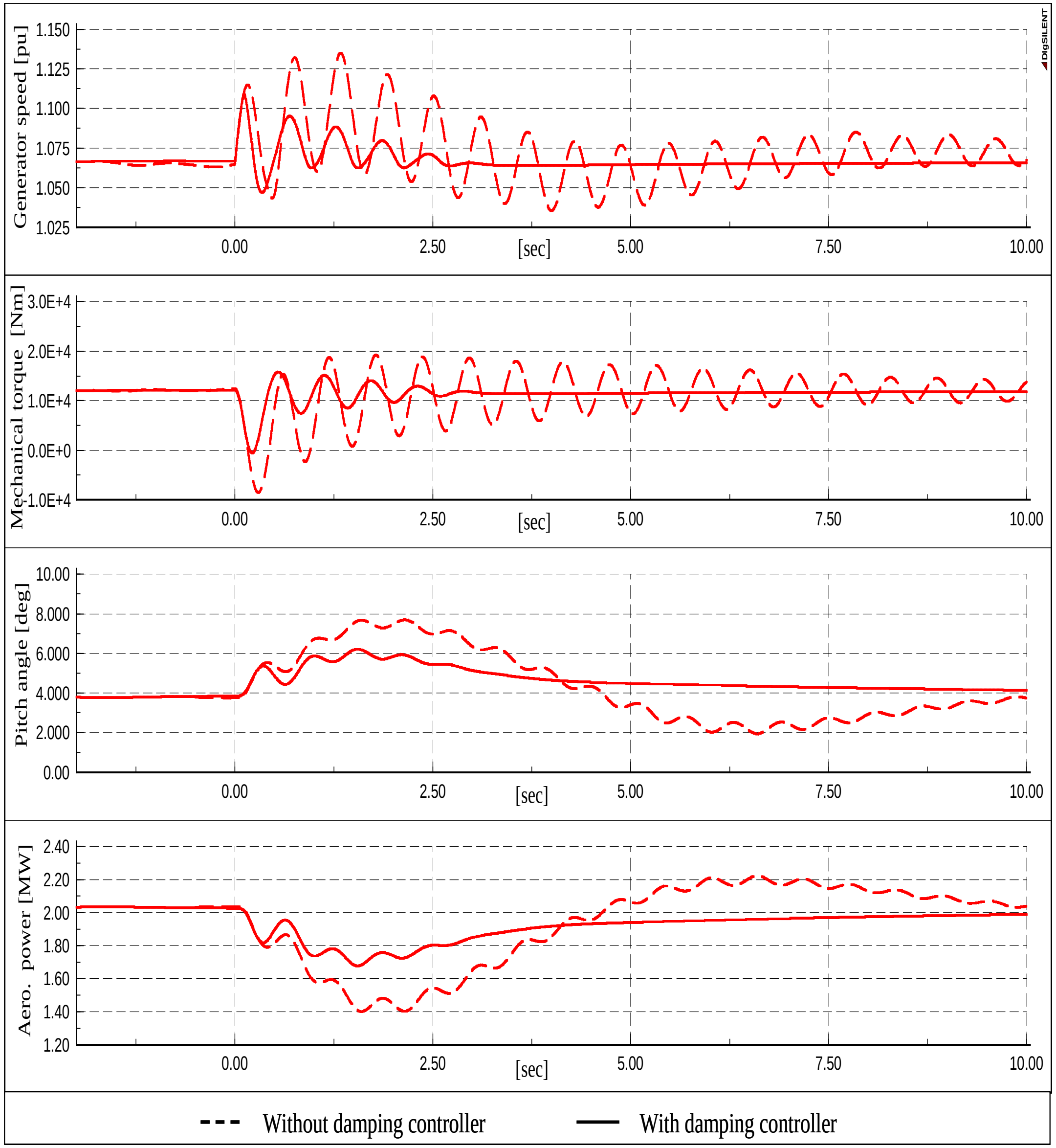
- On voltage dip:
  - RSC overcurrents
  - Crowbar activtates / RSC disconnects
  - DFG behaves as SCIG (no control)
  - GSC can still be used as a STATCOM



- Effect of increased crowbar resistance :
  - improves the torque characteristic
  - reduces reactive power demand
  - improves dynamic stability of the generator

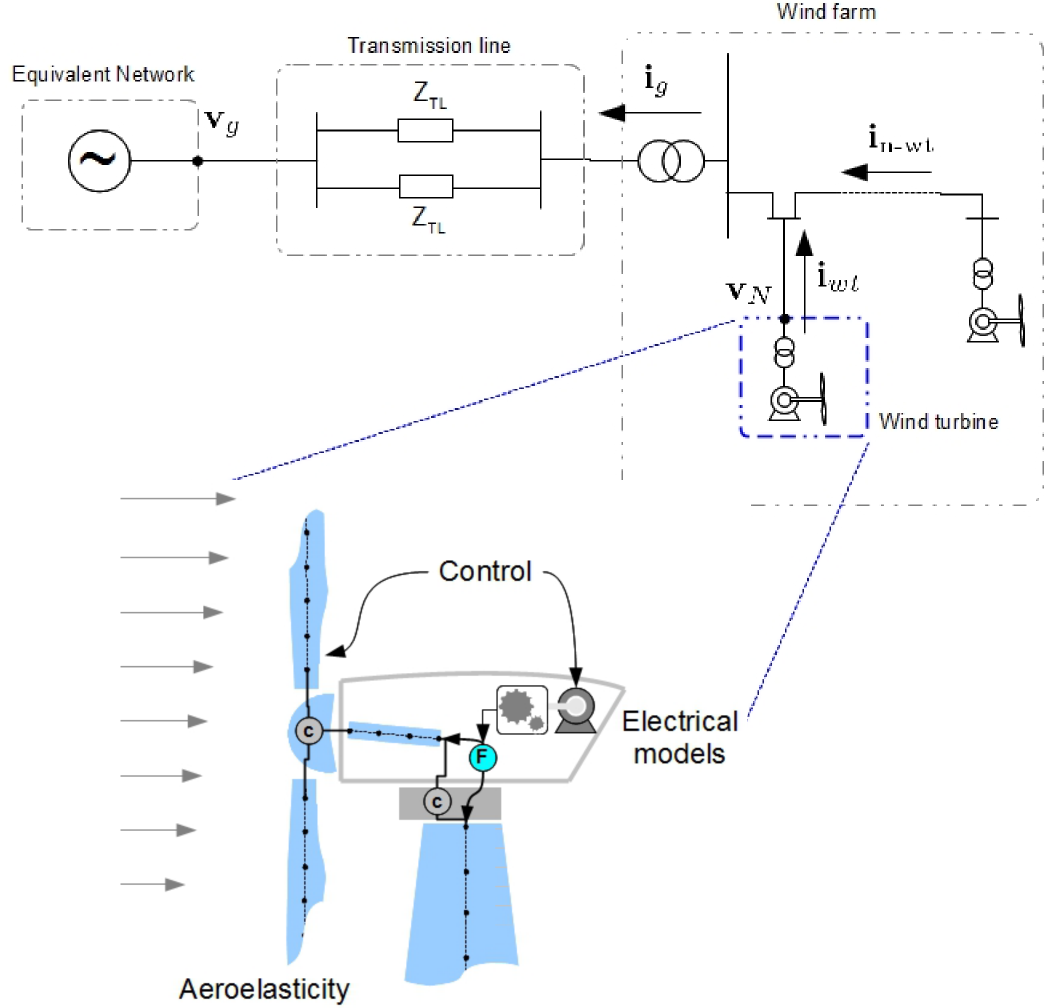
Load reduction – active damping



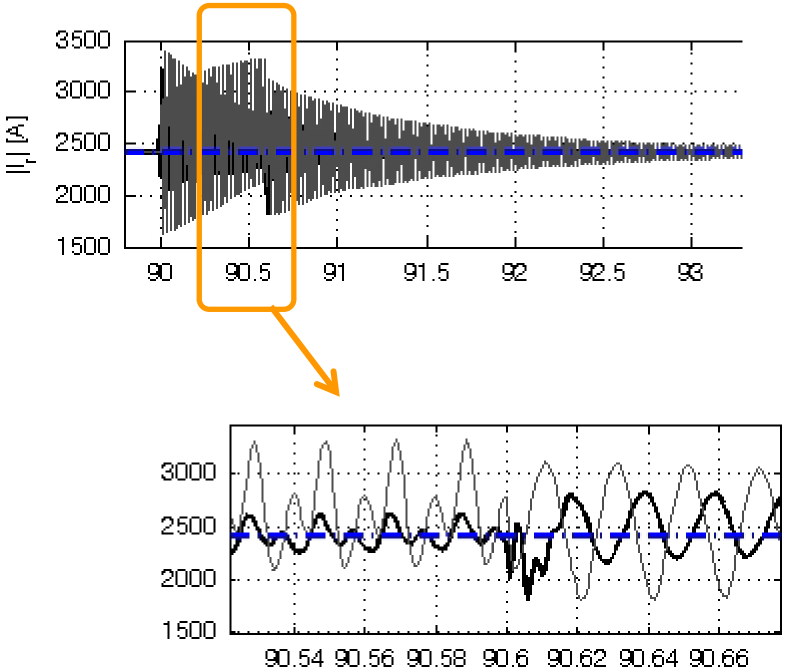


Integrated design analysis and load reduction

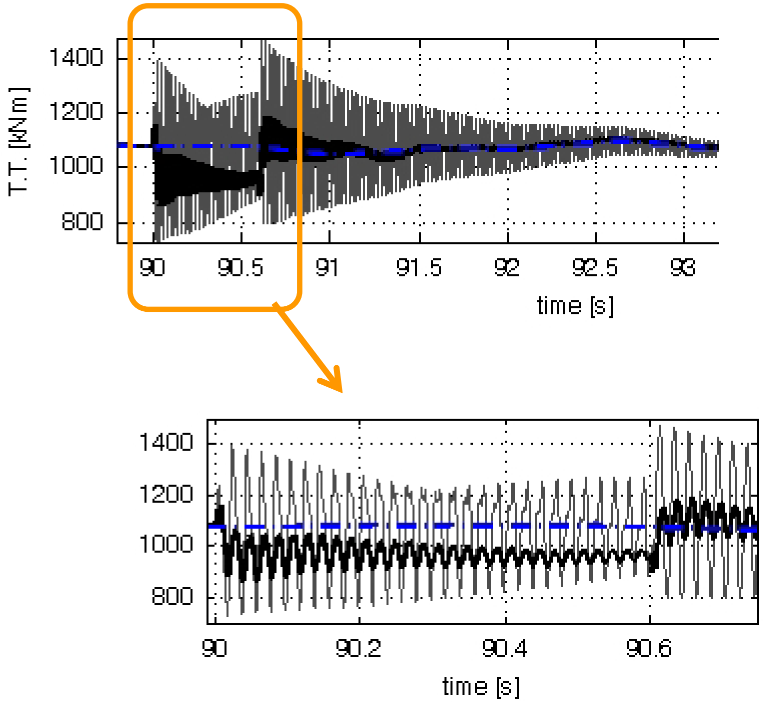
- Integrated analysis model
  - Aeroelastic model of wind turbine (HAWC2)
  - Pitch control
  - Asynchronous machine + control
    - Rotor and Stator fluxes
    - Current and power control of rotor side converter
    - Resonant damping control



Resonant damping control – load reduction Unbalanced fault

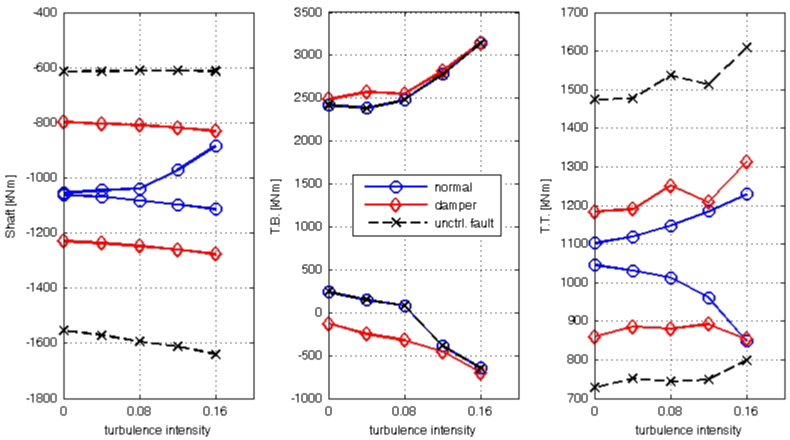


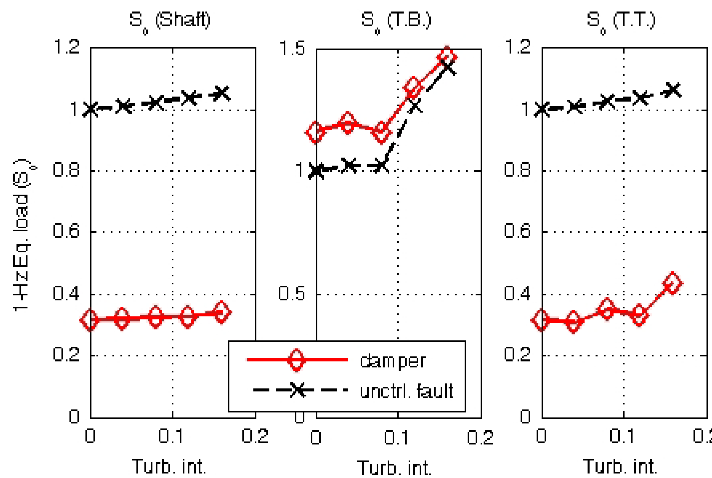
Electrical loads:
Generator rotor current



Structural loads:
Tower top side-to-side moment

Resonant damping control – load reduction



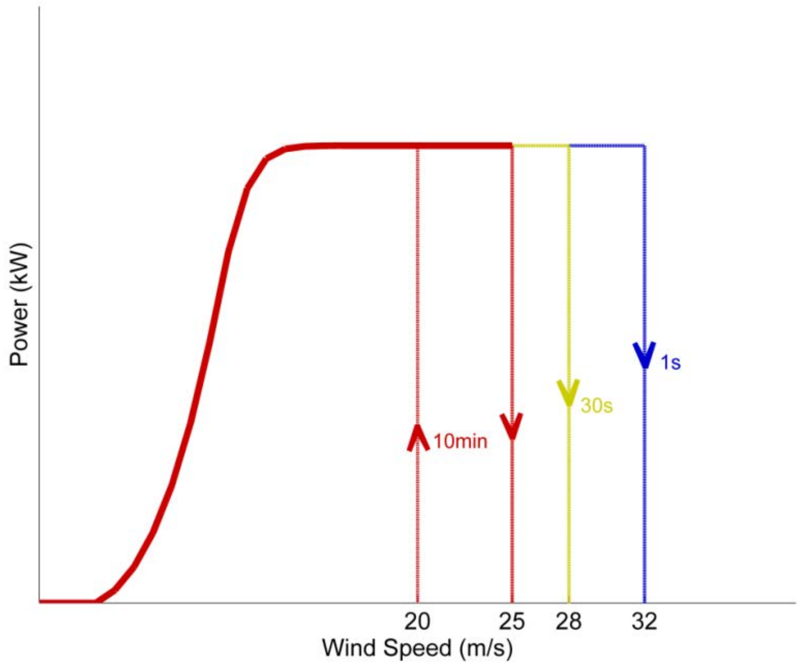


Load ranges
(max – min)

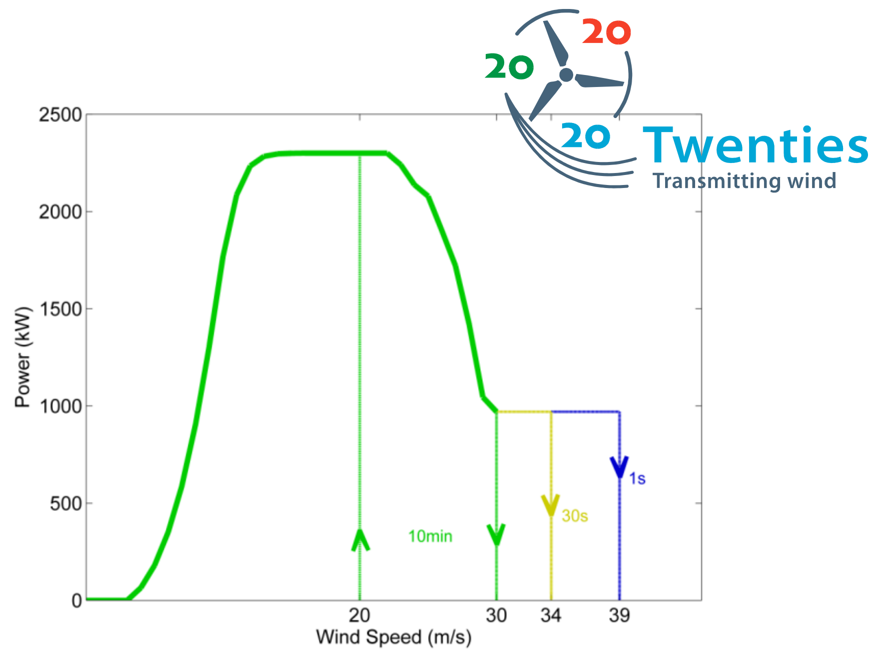
Equivalent loads
(fatigue)

Storm control

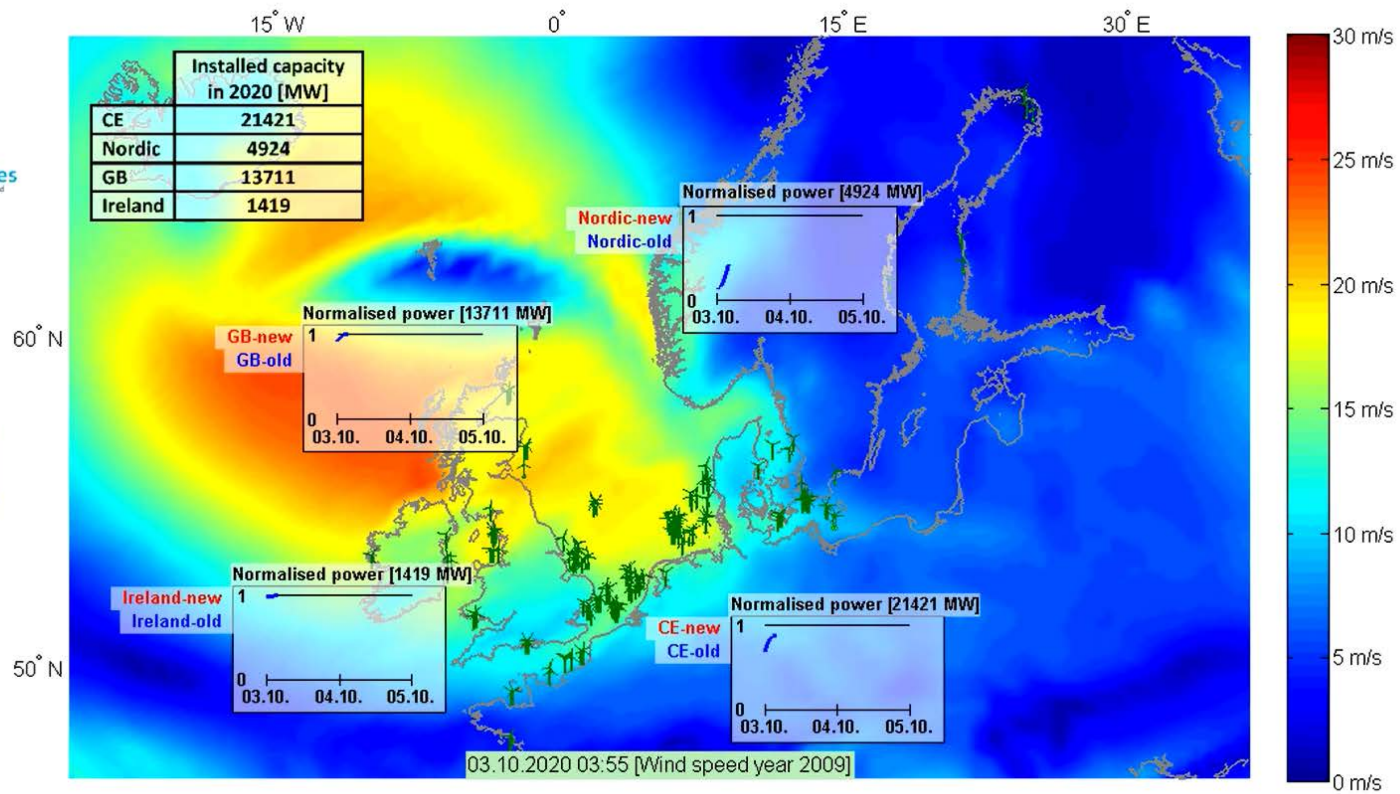
High Wind Shut Down



High Wind Ride Through (SIEMENS HWRT™)

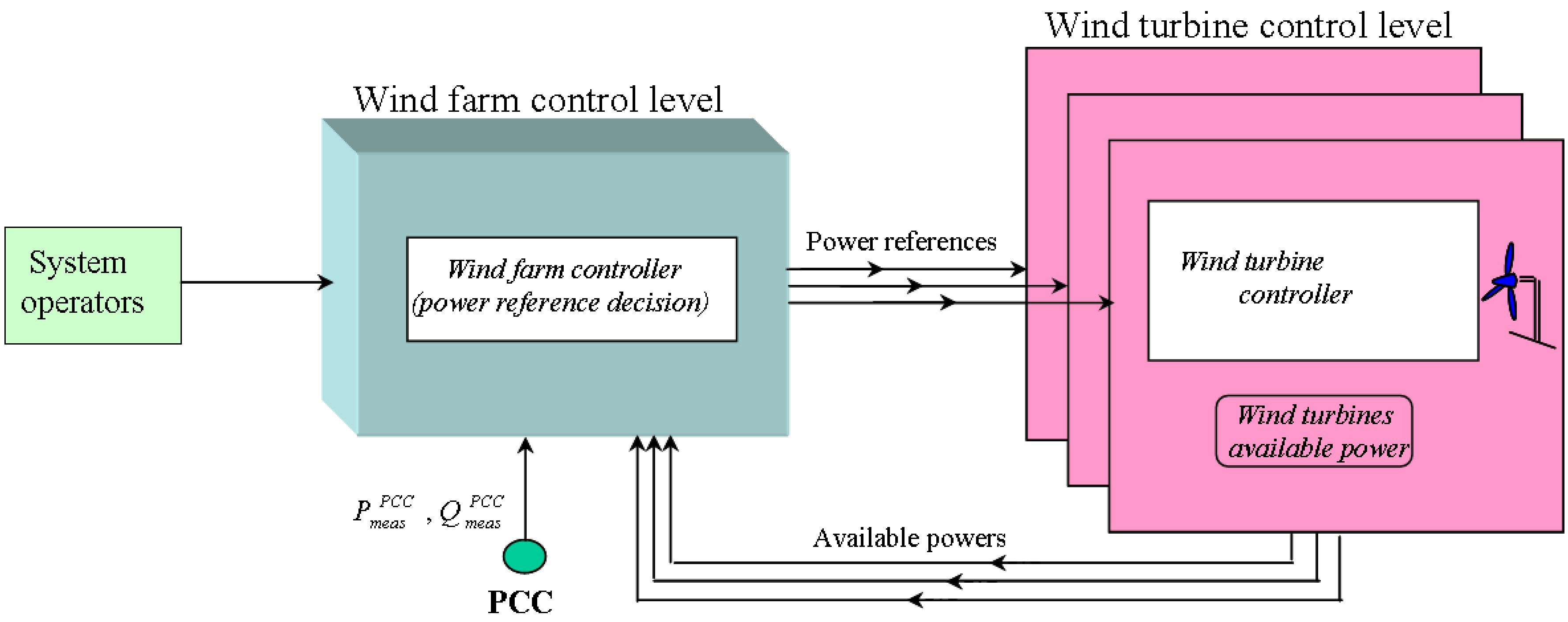


Offshore wind power variability 2020



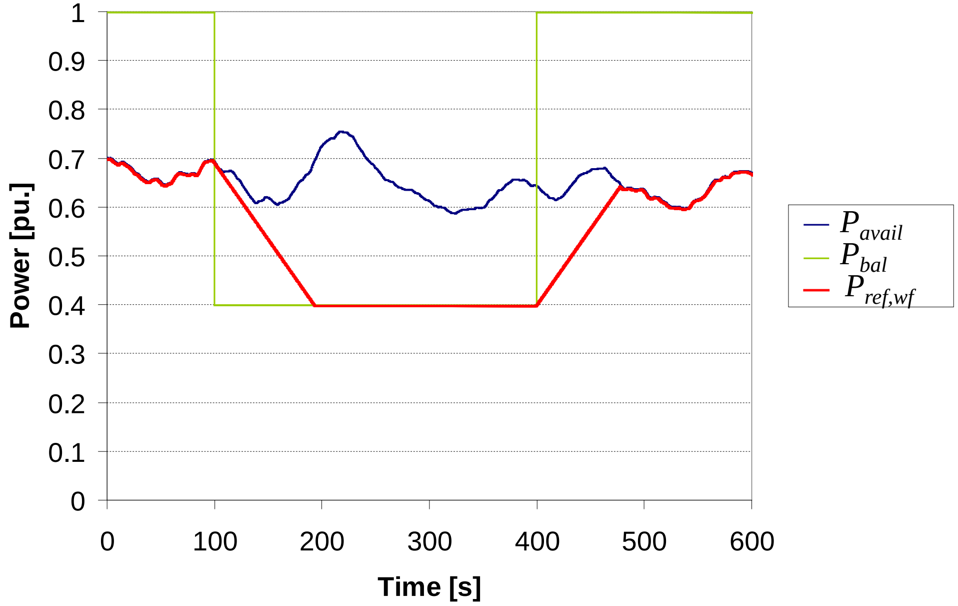
Wind farm control – wind power plants

- Contribute to control of grid voltage: amplitude and frequency, like other power plants
- Indirect grid control: active and reactive power control



Balance control

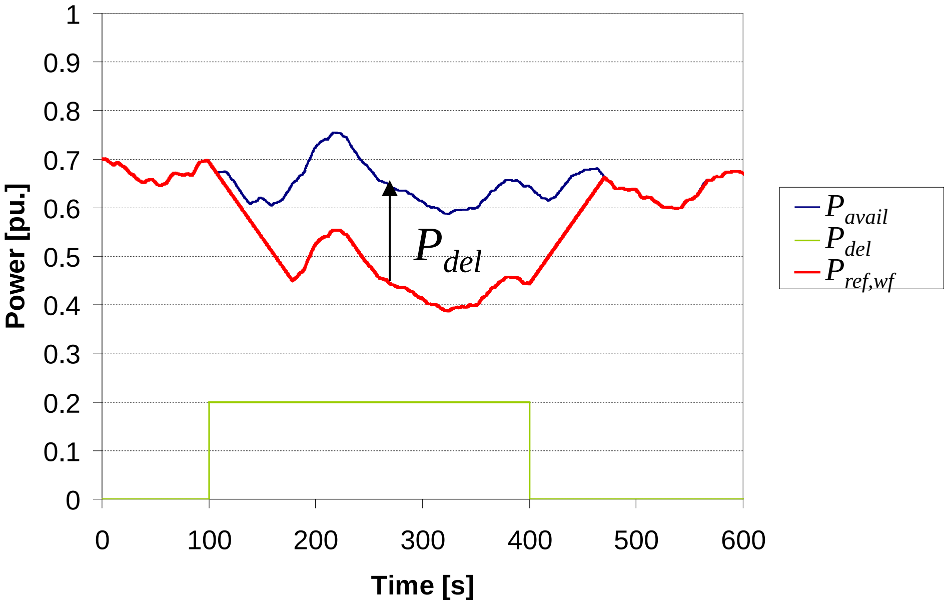
- Balance control provides
- Balance control already implemented in Horns Rev and Nysted
- Why ramp limitation

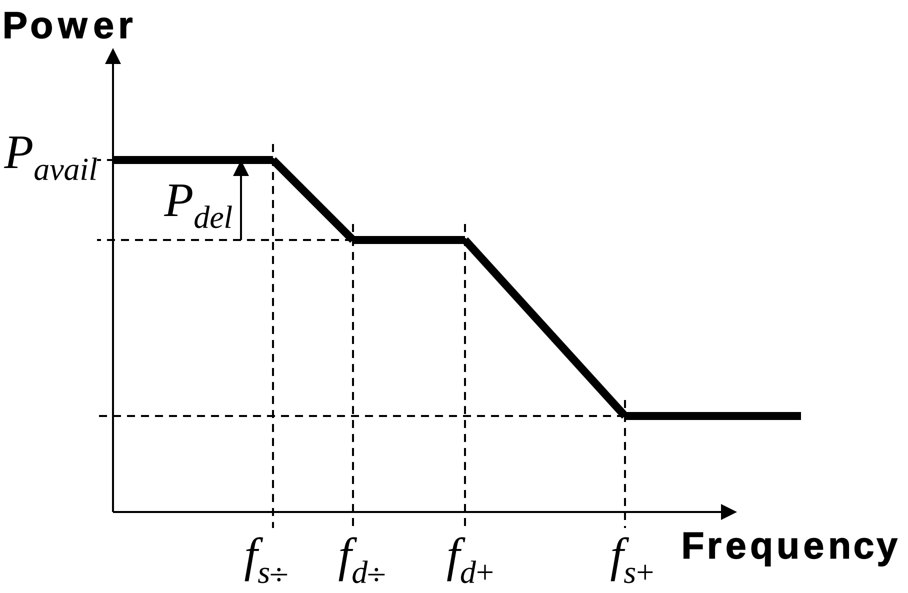


Delta control

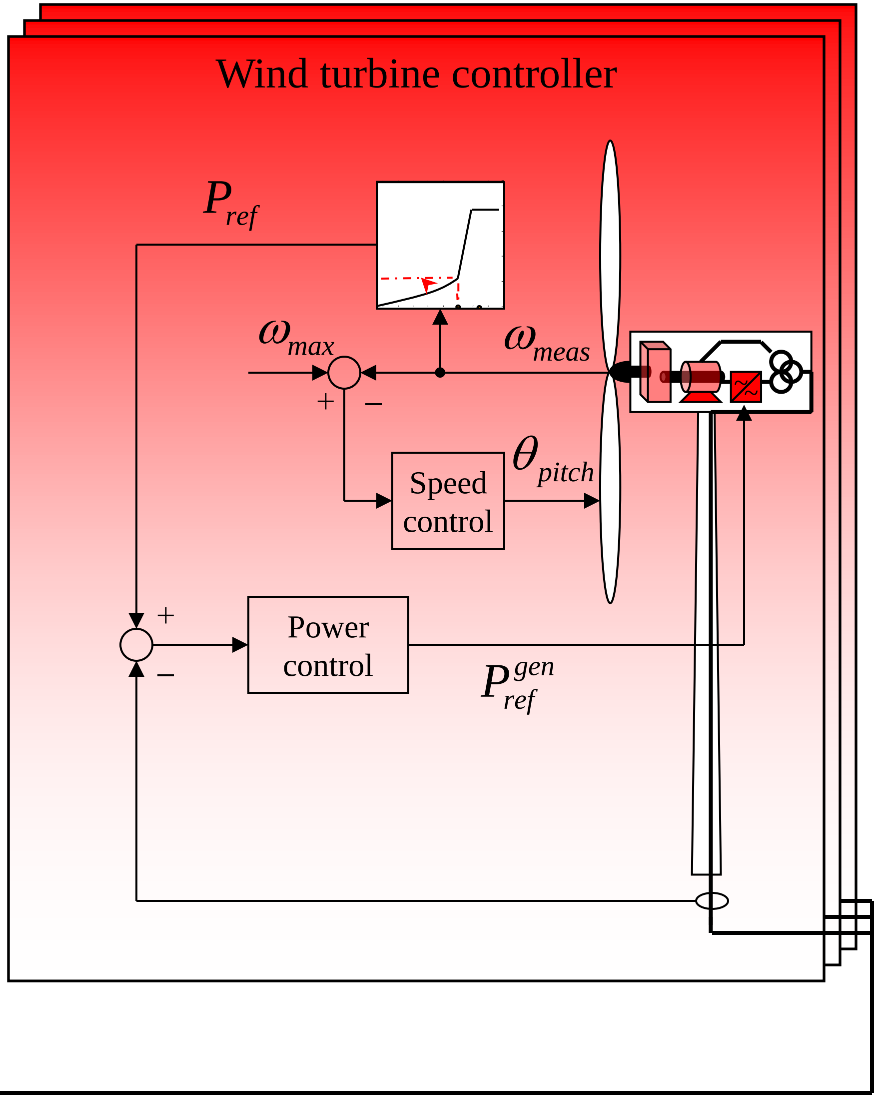
- Delta control provides fixed reserve
- Delta control already implemented in Horns Rev and Nysted

- Reserve can be utilised in frequency control (droop and deadband)

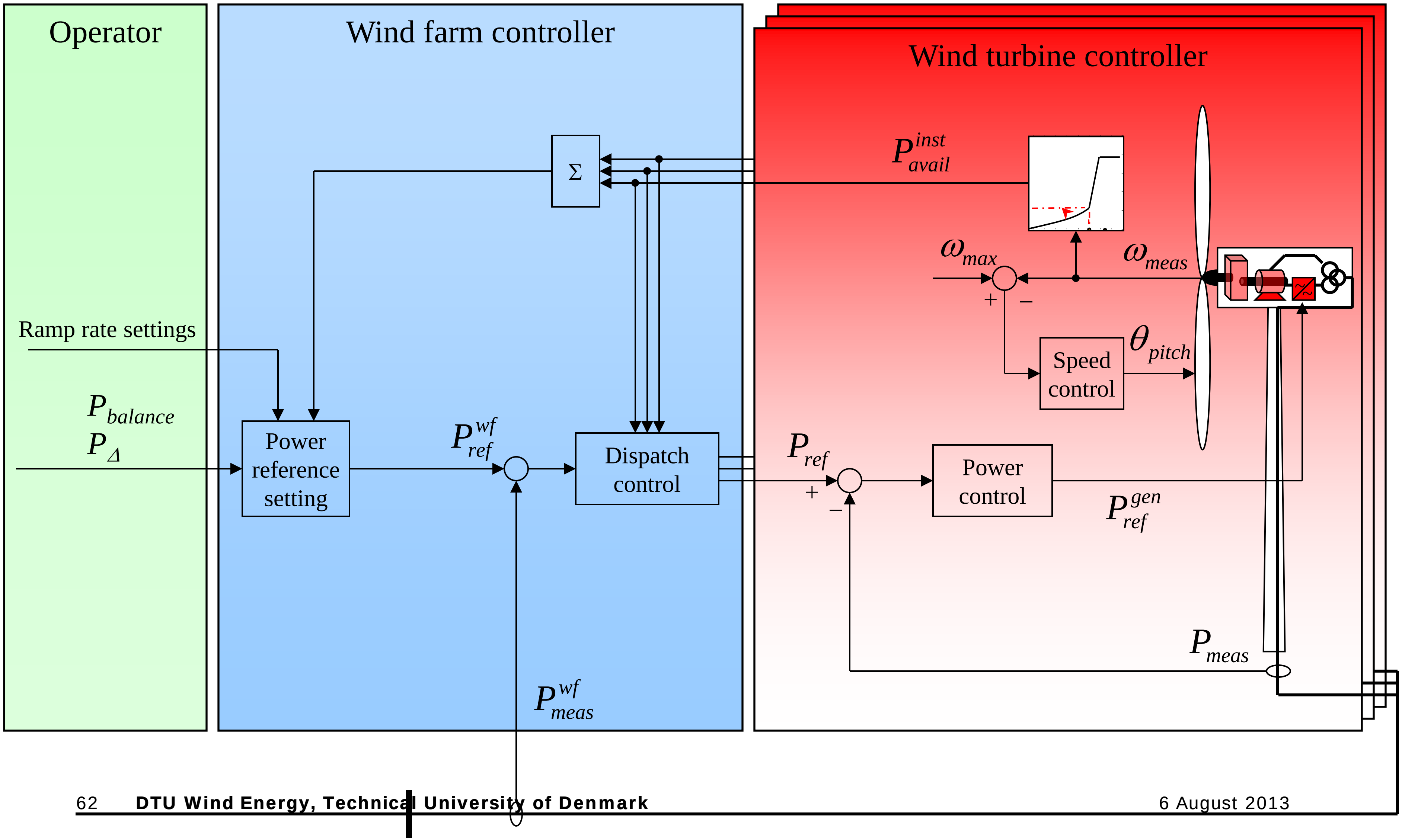




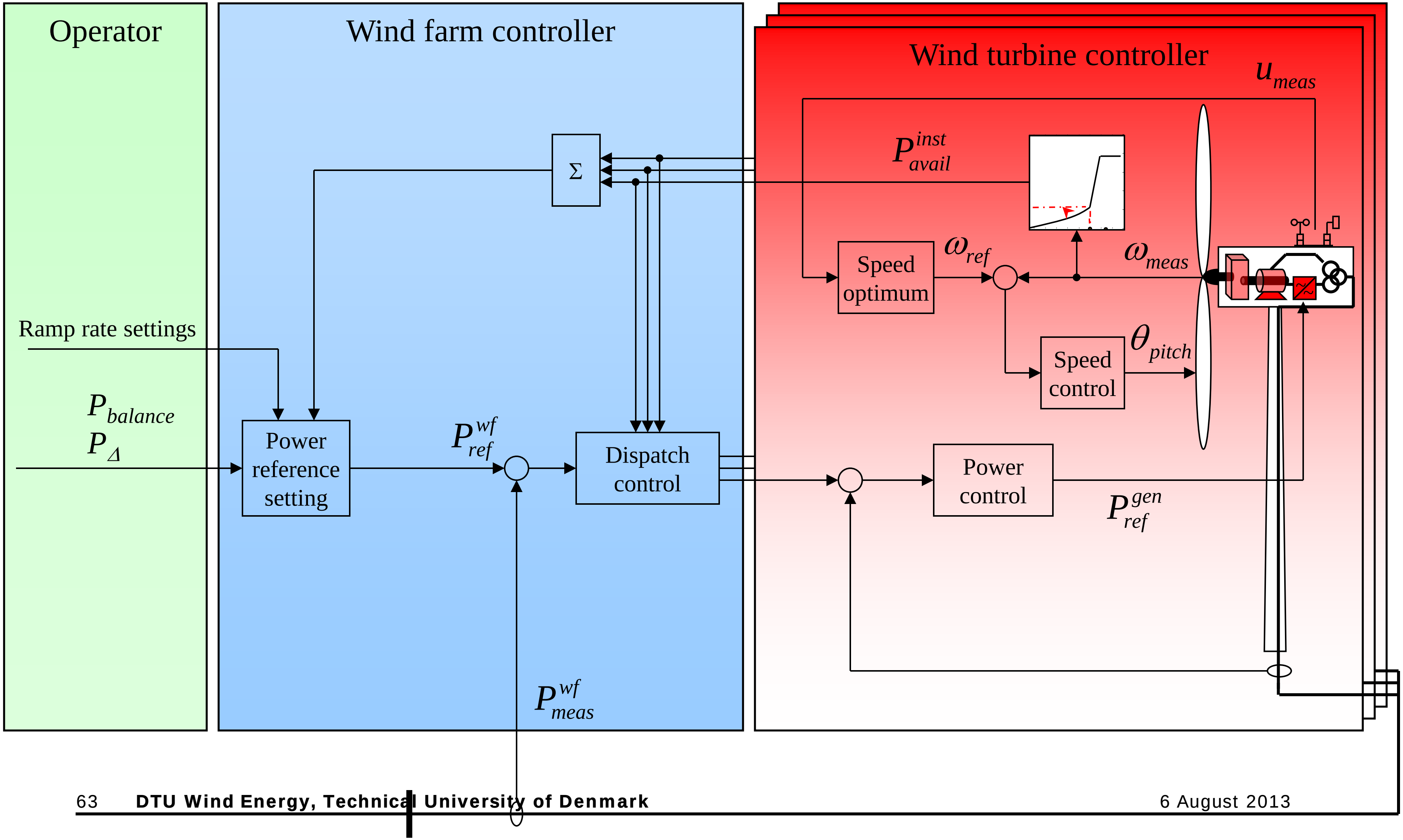
Double fed wind turbine – power control



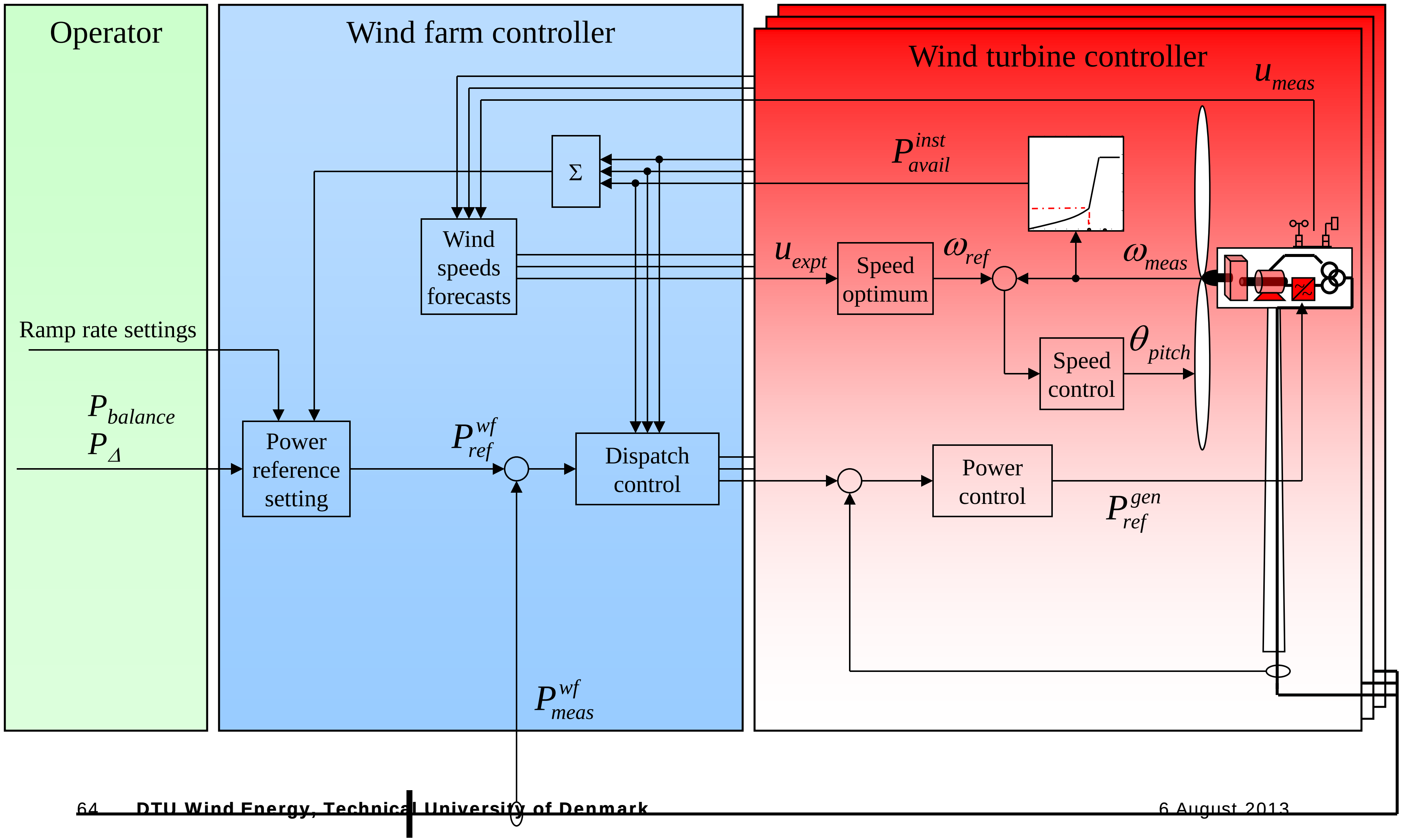
Double fed wind farm – power control



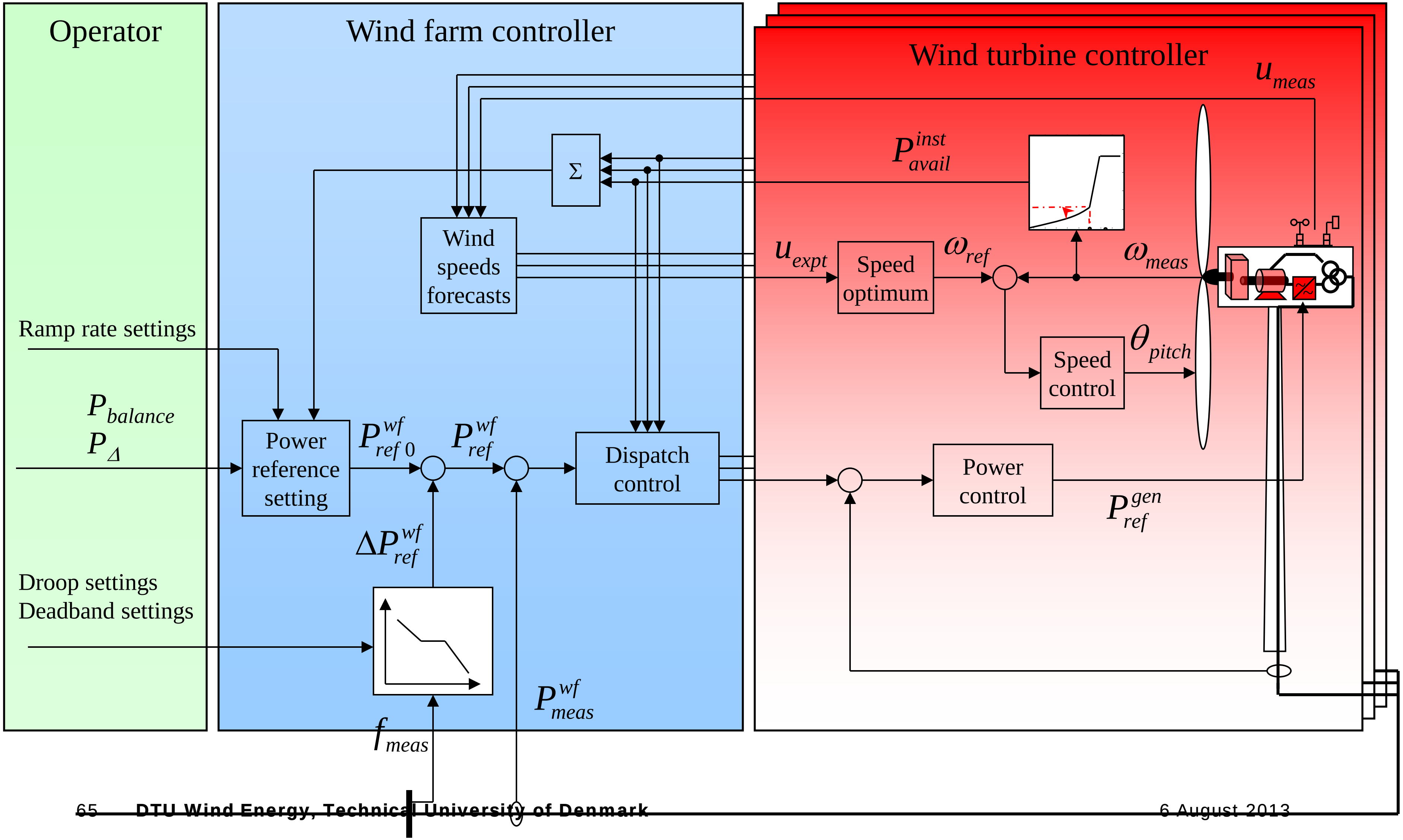
Double fed wind farm – power control



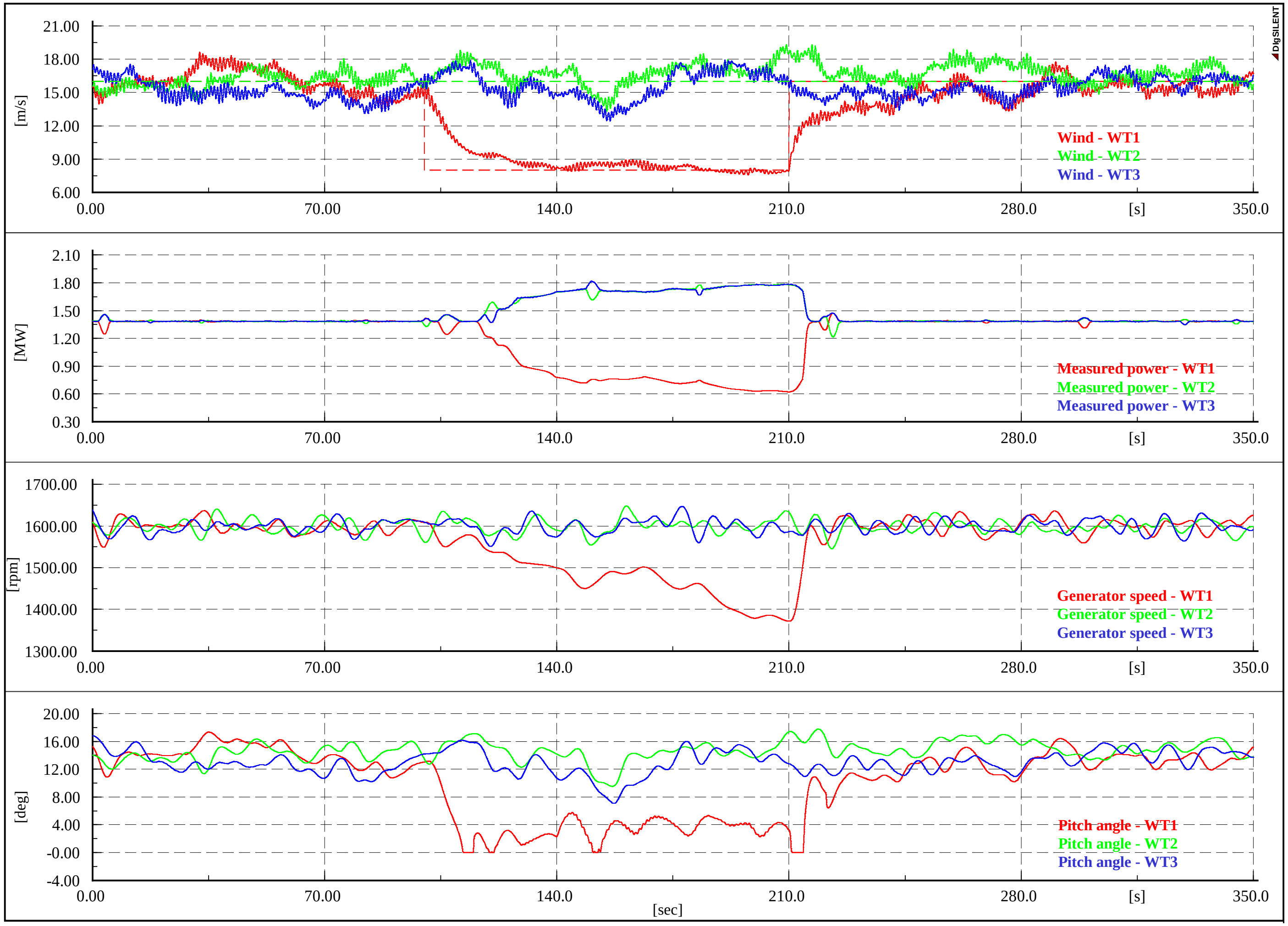
Double fed wind farm – power control



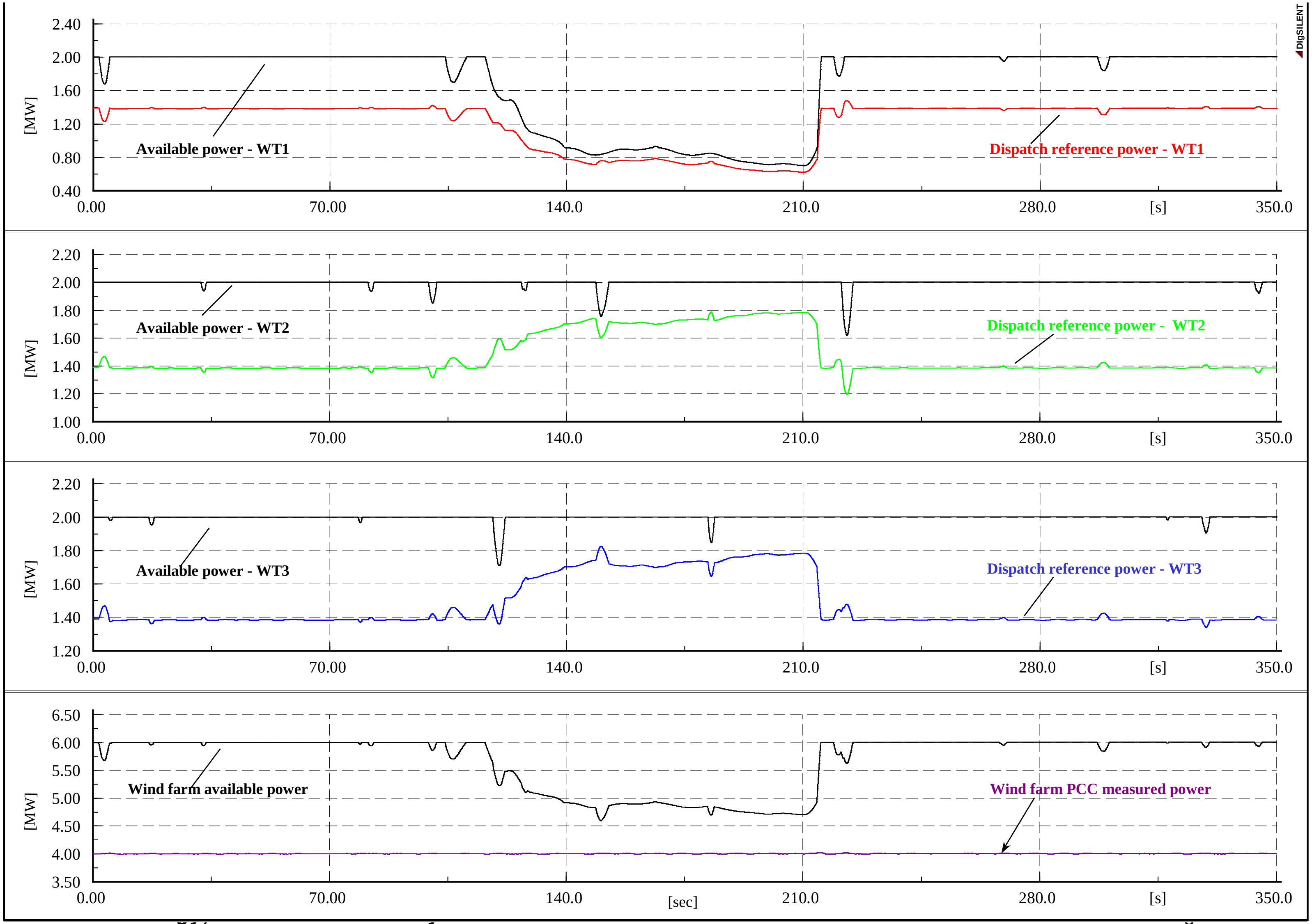
Double fed wind farm – frequency control



Wind farm power control – wind turbines



Wind farm power control



Summary / conclusions

- Control can
  - optimise production
  - reduce structural loads
  - support grid integration
- Controllability varies very much, depending on turbine design (fixed/var speed, fixed/var pitch)